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11. SUPPLEMENTARY NOTES

13. ABSTRACT (Maximum 200 words)

Regional seismograms from the Soviet JVE explosion were modeled. The explosion part of the source contained considerable RDP overshoot with possible spall contribution. The tectonic release part was composed of stress relaxation and secondary high frequency sources. Pn, Sn, Rayleigh and Love waves were modeled.

SsPmp phases were discovered in regional waves and modeled using ray theory and synthetic seismogram computations. SsPmp is an important wave in broadband data for event under the crustal waveguide but also occurs for crustal events under low velocity surface layers. When structure is known, SsPmp can be used as an added constraint on location of regional events.

Teleseismic source inversion using broadband SV waves was investigated. It was found that SV/SH inversion can constrain source radiation patterns as well as P/SH inversion although information on receiver structures is very important. Smaller earthquake events become accessible for waveform inversion using SV and SH waveforms.

Theory and computational methods were explored for the problems of plane wave propagation in plane layered, general anisotropic media and point sources in heterogeneous media. A teleseismic body wave inversion package was constructed for routine use.

14. SUBJECT TERMS

Regional Phases, Pn, Sn, Rg, Love, SsPmp; Telseismic P, SV, SH; Anisotropy, Reciprocity Theorem, Inversion, Explosions, Earthquakes

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Wave Propagation and Source Parameters in Eurasia

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Table of Contents

Executive Summary

At the beginning of the conception of this work in 1990, the direction of research in the seismic verification field was quickly being refocussed onto the issues of a proposed comprehensive test ban (CTB). Whereas past seismic research had been concerned with yield determinations from relatively large underground nuclear explosions, the proposed CTB significantly broadened the issues of event detection, location and identification. It became clear that possible violations of a CTB treaty would probably be associated with small events which could only be detected at regional distances. The related problems of event detection, location, and identification literally became entwined on the skein of complex, high frequency regional wave propagation. Although verification Seismology had made tremendous progress in teleseismic wave propagation for detecting, locating and characterizing seismic sources of all types, the interest in the regional wave propagation regime represented a significant challenge for solving the usual problems for smaller events at regional distances.

Work on this grant has concentrated on the problems of regional wave propagation although attention to teleseismic problems was also given. A major effort was made to understand the excitation and propagation of regional body and surface waves from the 1988 Joint Verification Experiment explosion in the Former Soviet Union. Broadband data written by the explosion on instruments deployed by the Natural Resources Defense Council were (and still are) unique in displaying spectacular, clear regional waveforms. Study of these data yielded provocative clues to the nature of both the seismic source and how waves propagated in the near-regional distance range. These results are summarized below and were published by Langston (1995).

1

An interesting regional phase for events occurring under the crustal waveguide was discovered by accident while reviewing data recorded by the IRIS GSN. It turns out that the phase SsPmp can be the largest arrival on a regional seismogram and complicates the interpretation of S waves. This phase is described by an SV wave which leaves upwards from the source, converts to a P wave at the free surface and then reflects from the Moho. Its large size is due to the combination of a large conversion coefficient at the free surface and to the fact that the resulting P wave reflection at the Moho is usually post-critical. An application of using this phase for earthquake location was described in the final report of a previous contract (Ecker, 1992). General characteristics and observations of SsPmp are described by Langston (1996) and are again summarized below.

Much of the seismicity in Eurasia is intraplate in type and often consists of small to moderate earthquakes which can only be recorded at a few teleseismic stations. It is often these very earthquakes which may be of the greatest interest in regional studies because they may be plentiful and yield high signal-to-noise signals at regional distances. However, the paucity of teleseismic data makes it difficult to obtain good source parameters such as source orientation, depth and time function. These are parameters which are very useful in understanding regional waves since the structure effect and the source effect must be separated. A study by Wang and Langston (1995) (see below) addressed the source inversion problem for combined inversion of SV and SH waves from earthquake sources. Because shear waves are more efficiently generated from earthquakes than are P waves, events with magnitudes less than 5.5 or so often write seismograms with well-defined S waveforms but not P waveforms. The governing equations for the response of a dislocation source show that the horizontal radiation pattern for SV and P waves is the same. Thus, it should be

possible to use SV and SH waveforms for determining source parameters in the same way that P and SH waveforms are used. However, most seismologists avoid using the SV waveform because of severe wave propagation effects due to the crustal waveguide which produces Shear-coupled Pl phases. Wang and Langston (1995) show that it is indeed possible to use broadband SV waves in a source inversion if reasonable receiver structures are available.

Two other topics in teleseismic wave propagation were addressed in an exploration of future wave propagation studies. In the first, Daejin Kang developed the equations needed to use the reciprocal theorem for constructing the far-field solution for a point source embedded in complex, 3 dimensional elastic media. The solution was checked using plane layer Thomson-Haskell theory. The reciprocal theorem makes it possible to perform far-field computations of point sources in heterogeneous media by using relatively simple numerical plane wave models. The direction of this research is pointed to using the theory with plane wave 3D finite difference calculations for study of the effect of lateral heterogeneity on far field body waves from earthquakes and explosions. The second theoretical topic considered was that of synthetic plane wave seismograms for layered anisotropic media. Daejin Kang extended the theory of Keith and Crampin (1977a;b;c) to include a free surface above a stack of layers over a halfspace. Synthetic seismograms for incident P, SV or SH waves can be computed for arbitrary elastic anisotropy. This technique will find use in interpretation of split teleseismic S waves, such as SKS, and modeling of anisotropic receiver responses.

Finally, the author spent time writing a comprehensive synthetic seismogram and inversion software package for analysis of teleseismic body waves. Certainly, this is not a new approach since the author has considered these problems since 1974. However, the package incorporates aspects of the

Joint Seismic Program Center (JSPC) database software package with a thorough synthetic seismogram calculator which makes broadband inversions fast and routine. It is also straightforward to use the package for regional waveforms with the addition of a suitable wavenumber integration code. The system was presented at an IRIS shortcourse on Moment Tensor Inversion given on the Berkeley, California, campus December 15 and 16, 1995. The tutorial is presented in the Appendix and the software will be publicly available from the IRIS DMS March 1996.

LIST OF PEOPLE INVOLVED IN RESEARCH EFFORT

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Ming Zhao	Graduate Student
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LIST OF PUBLICATIONS RELATED TO RESEARCH EFFORT

Clouser, R. H., and C. A. Langston, Effect of sinusoidal interfaces on teleseismic P wave receiver functions, Geophys. Jour. Int., 123, 541- (1995). (Carryover from a previous AFOSR Grant).

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Wang, M., and C. A. Langston, Use of broadband teleseismic SV waves in earthquake source studies, submitted to Bull. Seism. Soc. Am.

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Wang, M., and C. A. Langston, Use of broadband teleseismic SV waves in earthquake source studies, submitted to Bull. Seism. Soc. Am., (1995)

SUMMARY of

Anatomy of Regional Phases and Source Characterization of the Soviet Joint Verification Experiment, Underground Nuclear Explosion

by C. A. Langston

Broadband data from the NRDC deployment of stations in Kazakhstan at Karkaralinsk (KKL) and Bayanual (BAY) are subjected to detailed waveform modeling to understand the nature of regional wave propagation and to determine the nature of the explosion time function and sources of low- and high-frequency "tectonic release". Minor modification of a crustal model inferred from DSS studies in the region is very effective in explaining the arrival times, amplitudes, and waveshapes of the Pn and PmP arrivals at both stations. The SH-wave data are remarkable, however, for showing a large, high-frequency arrival after the expected and observed arrival of SmS from the explosion source. These secondary S arrivals imply a secondary source 1 to a few kilometers to the south of the shot point. Shear waves from this source dominate the seismic data at high frequency but are minor at low frequency where shear waves and surface waves from the inferred relaxation of the explosion cavity dominate the wave field. The secondary S-wave source is inferred to represent explosion-driven faulting with no net moment. Significant overshoot in the RDP is required to match the P-wave data. It is found that von Seggern-Blandford and Haskell source functions are incapable of producing the observed overshoot. However, the Mueller-Murphy source model is very effective in matching the clear overshoot effects seen in the P waves. Spall effects are also considered but appear to be minor and serve to require even more overshoot in the RDP. The

excitation and dispersion of Rayleigh waves in the period band of 1 to 10 sec is seen to be a sensitive, but nonunique, function of both Vs and Vp in the upper crustal layer. High Poisson ratios in this layer are needed to explain the Rayleigh waveform.

SUMMARY of

The SsPmp Phase in Regional Wave Propagation

by

Charles A. Langston

Regional broadband waveforms of deep- and intermediate-depth earthquakes written at College, Alaska, and Matsushiro, Japan, show large SsPmp phases that may be the largest phase seen on the seismogram. SsPmp is created when the direct, upgoing SV-wave converts to a P-wave at the free surface and subsequently becomes trapped in the crust because of postcritical P-wave reflection at the Moho. SsPmp may arrive between the P- and S-wave phases or it may arrive after S, depending on source depth and distance. Thus, it can be used as an additional constraint on source depth and location. It is important to recognize the existence of this phase since it is easily confused wiht the S-wave arrival, resulting in erroneous S-wave arrival time picks, or it may be interpreted as a split shear wave, incorrectly implying shear-wave anisotropy in the medium. Such a wave propagation effect will also be important for a crustal source for structures that contain low-velocity layers near the surface.

SUMMARY of

Use of Broadband Teleseismic SV Waves in Earthquake Source Studies

by

Mingguang Wang and Charles A. Langston

A generalized inverse technique utilizing a moment tensor formalism is applied to teleseismic, broadband SV, SH, and P wave data. The SV wave Green's functions are generated using the SKBJ spectral method, which allows the source and the receiver regions to have different structures and accurately simulates the wave propagation complexities of SPL and S-coupled P waves in the source and receiver areas. P and SH wave Green's functions are calculated by the generalized ray method. Comparison of joint P/SH, SV/SH and P/SV/SH source parameter inversions of the February 21, 1991, Bering Sea event and the April 25, 1992, Cape Mendocino, California event demonstrate that the SV waveform can effectively take the place of the P waveform in teleseismic source studies. However, receiver and source structural complexities produce poorer SV waveform fits, compared to P and SH fits. Joint inversion of all waveform data does best, however.

Teleseismic Body Wave Radiation from a Point Source in Three-Dimensional Heterogeneous Media Using the Reciprocity Theorem

by

Daejin Kang

1. Introduction

It is generally believed that scattered energy resulting from heterogeneity near the source, along the raypath, and near the receiver is related to waveform complexity. Recently, several studies have been conducted that address, in detail, the effect of seismic wave propagation through heterogeneous media (e.g., Vidale and Helmberger, 1988). These studies found that structural variations along the propagation path can have a profound effect on the amplitude and duration of the recorded seismic signal.

We focus our attention on the source region for these types of study. A point source is located at either in or near three-dimensional heterogeneous medium. Our objective is the determination of the far-field displacement produced by this source-medium interaction using the principle of seismic reciprocity.

The reciprocity theorem is a useful tool to study teleseismic radiation from seismic sources in the Earth's crust (White, 1960; Gupta, 1965, 1966, 1967; Ward, 1973; Bouchon , 1976; Mclaughlin et al., 1987, 1988). Though most of the results could have been obtained through solutions to the forward problem the reciprocal approach to the problem has the advantage of simplicity and may provide more physical insight. It is also applicable to the case where the source is located in general media (heterogeneous, anisotropic). In the forward problem the complications of the point source and the general media occur together, making the solution difficult. On the other hand, the approximate solution of the reciprocal problem is conceptually far easier to obtain. In the reciprocal problem the complications of the point source and the general media are separated. In this problem the point source occurs in a homogeneous region far from the general media. The wavefronts are approximately plane when they strike the heterogeneous and anisotropic zone. This response of the complicated media is more easily determined for incident plane waves. The complexity of scattering by the heterogeneous and anisotropic zone in the near-field of a point source is avoided by considering the reciprocal problem.

In the present study, we will show that the reciprocal approach to the problem - the inversion of

source and receiver through the reciprocity theorem - can lead to the same results in a much simplified manner. Examples presented in this proposal, however, are restricted to the flat layers with explosion source.

2. Purposes

The purposes of the proposed research are (1) to learn the details of earthquake and explosion sources (2) to determine earth structure and (3) from the knowledge of sources and structures, to predict the displacements at the surface of the earth from earthquakes and explosions. In particular, we will focus our attention on the effects of laterally varying complex structures in source region on radiated waveform and spectrum.

3. Reciprocal problem

Reciprocity is expressed as a symmetry of Green's tensor for linear elastodynamics. This result follows from the fact that the equations of motion in a linear heterogeneous, anisotropic elastic medium with homogeneous boundary conditions form a self-adjoint system. The theorem has been shown to hold for elastic waves (Knopoff & Gangi, 1959; Gangi, 1970). According to White (1960), the theorem of reciprocity may be stated as follows :

If in a bounded, heterogeneous, anisotropic, elastic medium, a transient force f(t) applied in some particular direction α at some point P (Fig. 1) creates at a second point Q a transient displacement whose component in some direction β is u(t), then the application of the same force f(t) at point Q in direction β will cause a displacement at point P whose component in the direction α is u(t).

We can express this reciprocity theorem in terms of Green's tensor. Consider the Green's tensor $G_{ni}(x,t;\xi,0)$ which represents the n-th component of displacement at position x and time t caused by the application of an instantaneous force of unit impulse in the i direction at position ξ and time 0. The reciprocity principle states that the following relation holds for the Green's tensor (Aki & Richards, 1980)

14

$$G_{ni}(\mathbf{x},t;\xi,0) = G_{in}(\xi,t;\mathbf{x},0) \tag{1}$$

In this proposal, we wish to use this reciprocity principle to simplify the determination of the far-field displacement from an explosive point source. A spherical explosive source of any extent is equivalent to three equal and mutually orthogonal force dipoles. Therefore, the moment tensor representation for the explosive source is given by (Geller, 1976)

$$u_n(\mathbf{x},t) = - [G_{n1,1} + G_{n2,2} + G_{n3,3}] * M_0 \tag{2}$$

Applying the reciprocity theorem, equation (1), to the Green's tensor in equation (2), we find that

$$u_n(\mathbf{x},t) = - [G_{1n,1} + G_{2n,2} + G_{3n,3}] * M_0 \tag{3}$$

This equation represents the n-th component of displacement at Q in the forward problem (Fig. 2) is obtained from the divergence of displacements at P in the reciprocal problem in which the source is a single point force at Q directed along the n-th axis.

4. Teleseismic body wave radiation from an explosive source in flat layered media.

Now, a simple example is presented which combines the reciprocity theorem and the flat layer theory to yield teleseismic body wave radiation from explosion.

Consider plane harmonic P waves of unit amplitude incident at an angle θ at the base of flat layered media. In each layer m, the resulting wave field will be a superposition of up- and down-going plane waves and corresponds to compressional and rotational displacement potentials of the form

$$\phi_m(x,z,\omega) = [A_{1m}\exp(-ik\gamma_{\alpha m}z) + A_{2m}\exp(ik\gamma_{\alpha m}z)]\exp(ik(ct+x))$$

$$\psi_m(x,z,\omega) = [B_{1m}\exp(-ik\gamma_{\beta m}z) + B_{2m}\exp(ik\gamma_{\beta m}z)]\exp(ik(ct+x)) \tag{4}$$

with

$$k = \omega/c$$

$$\gamma_{\alpha m} = (c^2/\alpha_m^2 - 1)^{1/2}$$

$$\gamma_{\beta m} = (c^2/\beta_m{}^2 - 1)^{1/2}$$

where α is the compressional velocity, β the shear velocity and c the phase velocity.

The coefficients A_{km} and B_{km} are easily determined using the Thomson-Haskell matrix formulation (Thomson, 1950 ; Haskell, 1953).

If u denotes the resulting horizontal displacement at a point P (Fig. 2) the reciprocity theorem implies that a horizontal unit force applied at P will produce at Q a displacement u in the θ-direction. Differentiating u with respect to x will then yield the contribution from a horizontal unit force dipole acting at P. Similarly, the contribution from a vertical force dipole will be given by the z-derivative of the vertical displacement v at P. Therefore, a spherical explosive source with spectral seismic moment $M_0(\omega)$ will produce at Q a radial spectral displacement

$$u_r(\omega) = \left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} \right] M_0(\omega) \tag{5}$$

that is, x and z being the source coordinates

$$u_r(\omega) = -\frac{\omega^2}{\alpha_m{}^2} M_0(\omega) \ [A_{1m}exp(-ik\gamma_{\alpha m}z) + A_{2m}exp(ik\gamma_{\alpha m}z)]exp(ik(ct+x)) \tag{6}$$

The tangential displacement u_θ can be obtained in the same way by computing the amount of dilatation produced by a unit force applied at Q along the direction perpendicular to $\mathbf{r}$. The incident wave is now an SV wave.

5. Numerical computations

We will only give numerical results for the explosive point source as the simplest type. But they will serve as guide to prove how to simplify the forward problem using the reciprocity theorem.

For a teleseismic body wave calculation, an explosive point source is set in a layer over half-space. This source is driven with a Gaussian time function given in Figure 3. The model used in this calculation

is given in Table 1. We wish to compute far-field displacements from an explosive point source in a layer using the reciprocity theorem. In the reciprocal approach, plane P or SV wave is directed from the half-space. Using the Thomson-Haskell matrix method, the horizontal and vertical transfer functions are computed at the source position (Fig. 4 (a) & (b)) and then the resultant P or SV wave responses are computed by applying the reciprocity theorem to these transfer functions (Fig. 4 (c)). These resultant responses are the responses at the half-space caused by the explosive point source in a layer. In Figure 5, we compare P wave response computed from the reciprocal approach with that computed from the forward approach. For the forward problem, we used Fuchs' expressions. He(1966) derived analytical expressions for the transfer function for dilatational body wave radiating into the mantle from a point source in a layered crust using the Thomson-Haskell matrix. This result shows that the response computed from the reciprocal approach is equivalent to that computed from the forward approach.

On the basis of this reciprocal approach, we consider the influence of the angle of incidence into the half-space and the source depth. The P wave responses have been determined for angles of incidence ranging from $5°$ to $50°$ at a fixed source depth, 2 Km (Fig. 6). It may be concluded that the P wave incident into the half-space at various angles does not vary significantly with angle of incidence. We will now place the source at six different depths : 0.5, 1, 2, 4, 7 and 10 Km (Fig.7). The angle of incidence into the half-space is chosen as $15°$. This result shows that the P wave response for an explosive source in a layer may be rather sensitive to changes in the depth of source.

6. Future research

(1) The reciprocal approach for dislocation source in homogeneous layered media

(2) The reciprocal approach for explosion source in three-dimensional heterogeneous media

(3) The reciprocal approach for dislocation source in three-dimensional heterogeneous media

(4) The application of this reciprocal method to teleseismic data

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Forward problem

Reciprocal problem
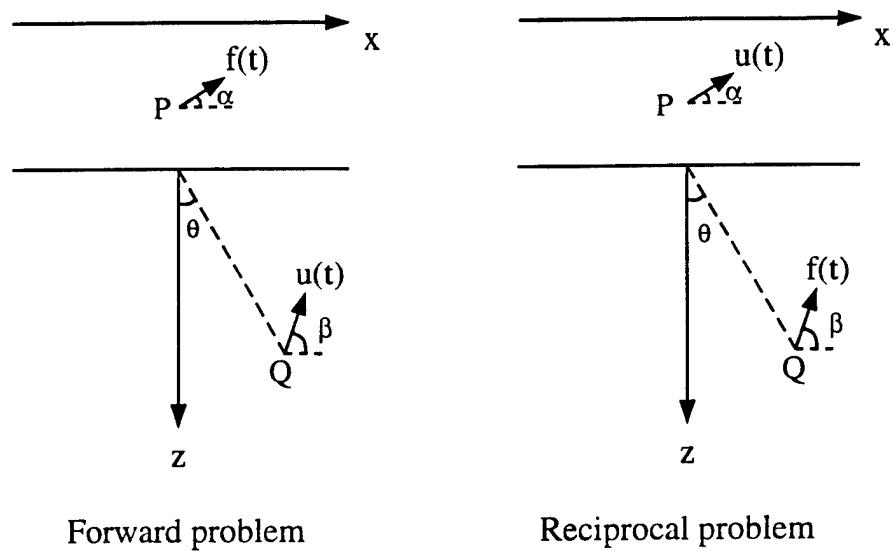
Figure 1. Reciprocity principle. Relation between the force f(t)
and an induced displacement u(t).
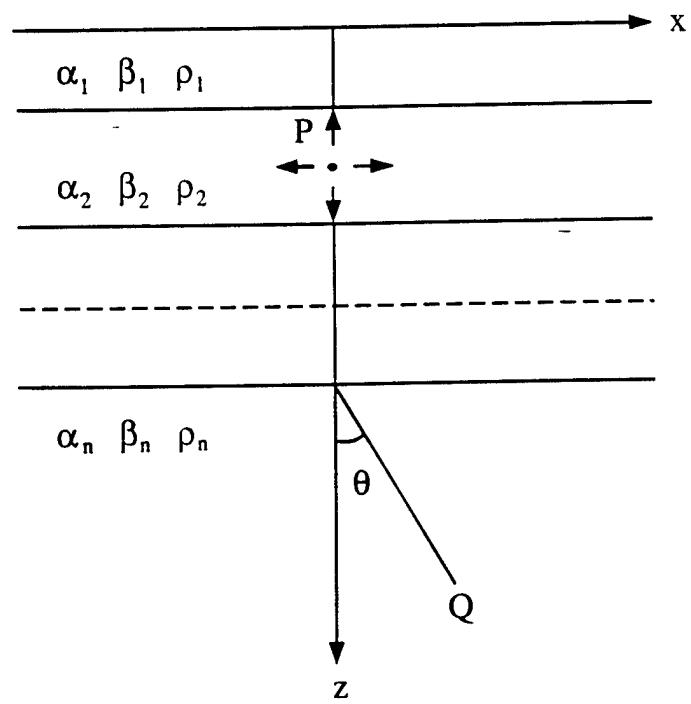
Figure 2. Geometry of the problem

P-wave velocity (Km/sec)	S-wave velocity (Km/sec)	density (g/cm³)	layer thickness (Km)
6.0	8.0	2.9	30
8.6	4.7	3.2	—

Table 1. Layer over half-space model
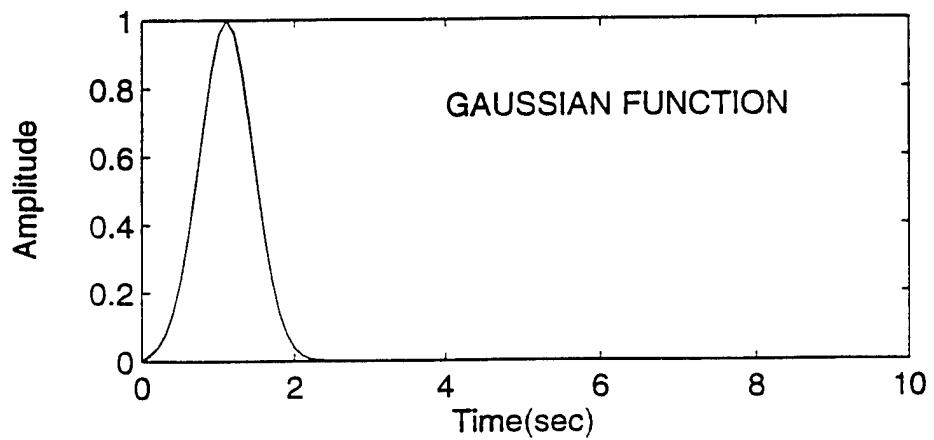
Figure 3. Incident wave time history.
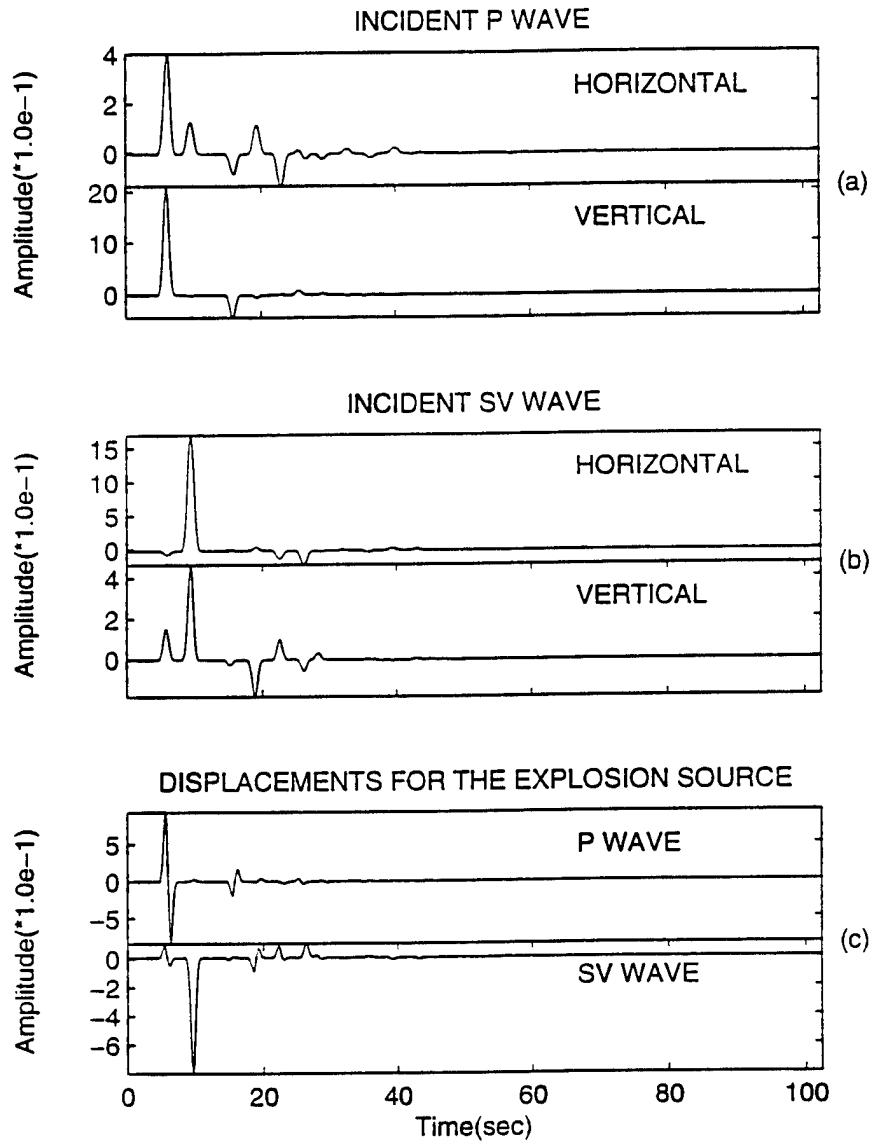
Figure 4. Horizontal and vertical transfer functions computed from the reciprocal approach and the resultant P and SV wave displacements computed by applying the reciprocity theorem to these transfer functions. The angle of incidence is 15° and the source depth is 1 Km. The model used is given in Table 1.

(a) the transfer functions for the incident P wave.

(b) the transfer functions for the incident SV wave.

(c) the resultant P and SV wave displacements.

P WAVE DISPLACEMENTS FOR THE EXPLOSION SOURCE
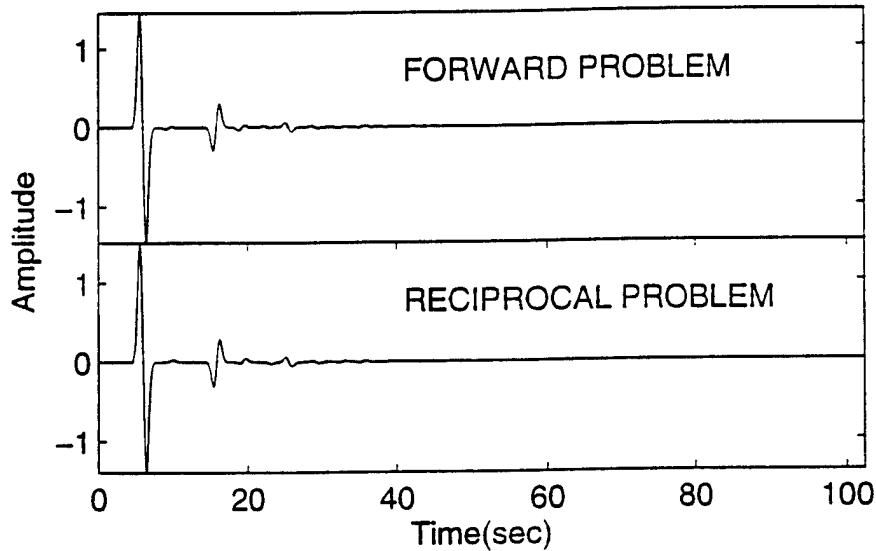
Figure 5. A comparison of the synthetic P waves computed from the forward problem and from the reciprocal problem. The angle of incidence is 15° and the source depth 2 Km. The model used is given in Table 1.
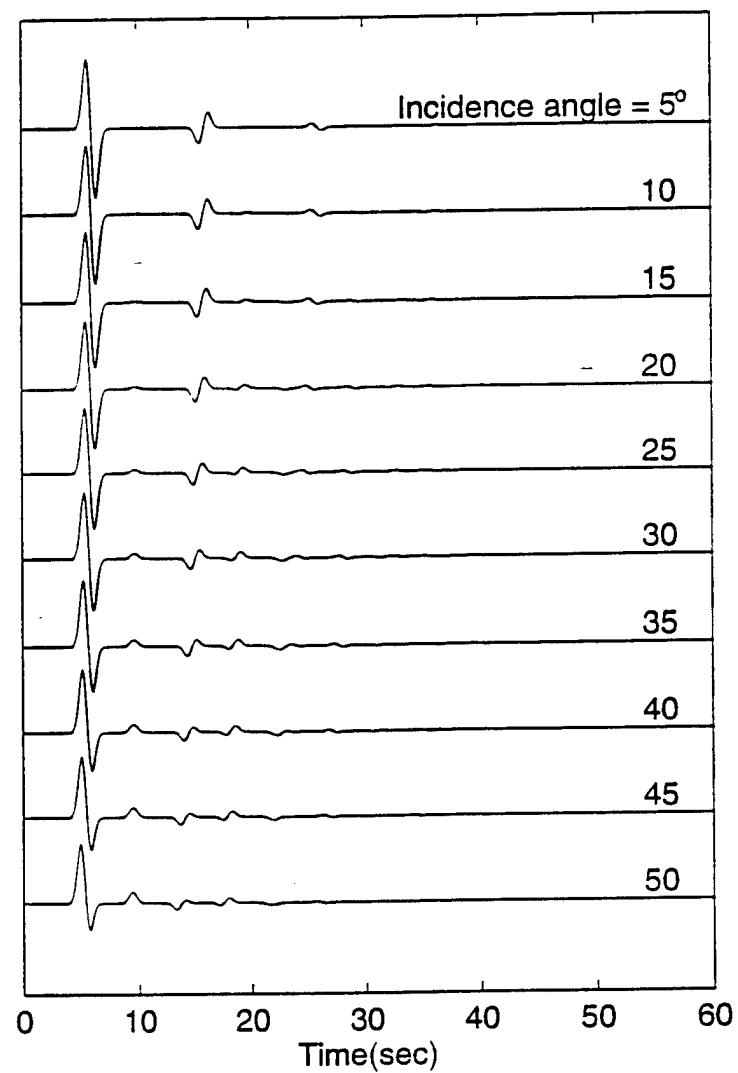
Figure 6. P wave responses at the source depth, 2 Km, at various incidence angles. The angles of incidence range from 5° to 50° with interval 5°. The model used is given in Table 1.
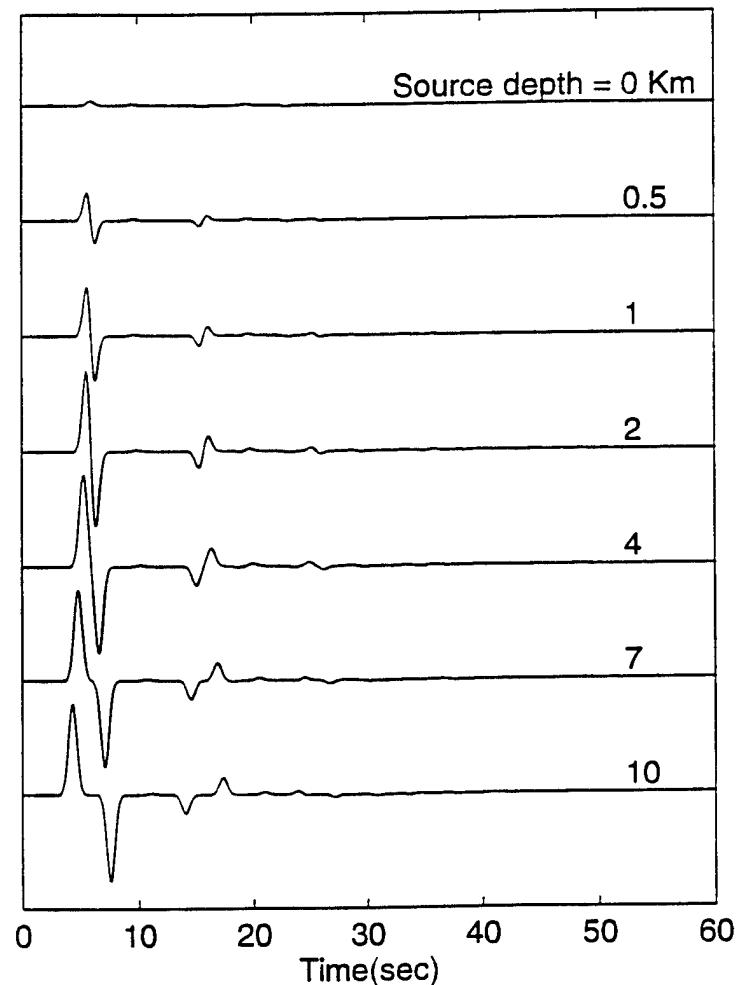
Figure 7. P wave responses at the angle of incidence, 15°, at various source depths. The source depths are 0 , 0.5, 1, 2, 4, 7 and 10 Km. The model used is given in Table 1.

Synthetic Body-Wave Seismograms in Anisotropic Media

by

Daejin Kang

We investigate theoretically the effects of anisotropy by calculating synthetic seismograms for simple plane-layered structures with a free surface. For the theoretical part of our work, we take as our basis the work of Taylor & Crampin (1978).

(1) Theoretical aspects

We consider an n layered half-space, with the axes, and the layer and interface numbering arranged as Fig. 1. The direction of the apparent velocity c along the surface is confined to the x_1 direction, and all the elastic tensors are rotated accordingly.

From the elastodynamic equations of motion,we obtain a matrix equation for p, frequently called the slowness equation:

$$\mathbf{Fa} = (\mathbf{R}p^2 + \mathbf{S}p + \mathbf{T} - \rho c^2 \mathbf{I})\mathbf{a} = \mathbf{0}, \tag{1}$$

Since $\mathbf{R}$ is non-singular, equation (1) can be written in partitioned matrices as a linear eigenvalue problem for p:

$$\left[\begin{pmatrix} -\mathbf{R}^{-1}\mathbf{S} & -\mathbf{R}^{-1}\hat{\mathbf{T}} \\ \mathbf{I} & \mathbf{0} \end{pmatrix} - p \begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{pmatrix} \right] \begin{pmatrix} \mathbf{a}p \\ \mathbf{a} \end{pmatrix} = 0 \tag{2}$$

The solution of the slowness equation in the form of the eigenvalue problem and simple scaling of the eigenvectors using the orthogonality of the row and column vectors for eigenvalues allows us to construct the propagator matrices of Gilbert & Backus (1966) without numerical inversion.

The product of the propagator matrices relates the displacement-stress vectors at the top of the half-space to those at any other interface. The solution is determined by relating the half-space vector to the boundary conditions at the free surface, where the components of normal stress vanish. We have

$$(\delta_{1k}, \delta_{2k}, \delta_{3k}, f_4, f_5, f_6)_n^T = E_n^{-1} G (u_1, u_2, u_3, 0, 0, 0)_0^T \tag{3}$$

where $G = \prod_{m=n-1}^{1} G_m$

(2) Results of calculations

The incident pulse to be transmitted through the structure from the lower half-space is given by

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Fig. 2. In this paper the models given by Table 1 are investigated. The anisotropic media in these models are transversely isotropic medium (Table 2 (a)) and the anisotropic medium with the (001)-cut orthorhombic olivine (Table 2 (b)). In our models we take the axis of symmetry in the plane (x_1, x_2), making an arbitrary angle ϕ with the x_1-axis, i.e., to the horizontal projection of the wave propagation direction. The angle ϕ is reckoned from the x_1-axis in an counter-clockwise sense when viewed from above.

Figure 3 shows the dependence of the velocity of each body wave on the propagation direction in the transversely isotropic medium and the anisotropic medium with (001)-cut orthorhombic olivine given in Table 2.

We now examine the synthetic seismograms computed for the models in Table 2 with plane body waves of the three types P, SV, and SH approaching from the isotropic half-space. The most common property of all in the synthetic seismograms is the presence of the traces of the three wave types, P, S_1, and S_2 on every component (Fig. 4 & 5). While propagating along the layer, the P, S_1, S_2 waves, by virtue of their velocity differences, arrive at different times and manifest themselves as separate incidences on the seismograms. For the case of the incident P-wave, the presence of anisotropy couples the P, SV and SH wave motion so that P waves incident on the anisotropy layer from below produce P, SV and small-amplitude SH waves at the surface. In the case of incidence of the SV and SH waves on the lower interface, the anisotropy of the layer manifests itself most distinctly in the splitting up of the SV and SH waves into S_1 and S_2 waves at the lower interface, the latter having different velocities. The ratio of the amplitudes of the S_1 and S_2 waves strongly depends on the angle ϕ.

From these results, we can infer that the effects of anisotropy on incident P waves are small, while the effects on incident S waves are comparatively large.

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Notations

a   the amplitude vector, with elements $\{a_j\}$, of a particular plane wave decomposition

c_{jkmn} the elements of the elastic tensor, not necessarily referred to the principal axes

f the vector of excitation functions with elements $\{f_j\}$, j=1,2,....,6

I   the 3×3 identity matrix

p the normalized slowness vector

R, V, and T   submatrices of the full elastic tensor, with elements $\{c_{j3k3}\}$, $\{c_{j1k3}\}$, and $\{c_{j1k1}\}$, respectively

S $= \mathbf{V} + \mathbf{V}^T$

T^ $= \mathbf{T} - \rho c^2 \mathbf{I}$

δ_{jm} the Kronecker delta function

ρ density

ω the angular frequency

G   the propagator matrix which is expressed by $G_n = E_n D_n E_n^{-1}$

where

$$E_n = \begin{pmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{R} & \mathbf{V} \end{pmatrix} \begin{pmatrix} \mathbf{AP} & \mathbf{A'P'} \\ \mathbf{A} & \mathbf{A'} \end{pmatrix}$$

$$E_n^{-1} = \begin{pmatrix} \mathbf{AP} & \mathbf{A'P'} \\ \mathbf{A} & \mathbf{A'} \end{pmatrix}^T \begin{pmatrix} -\mathbf{V} & \mathbf{I} \\ -\hat{\mathbf{T}} & \mathbf{0} \end{pmatrix}$$

$$D_n = \text{diag}[\exp(-i\omega p_j d_n/c)]$$

d_n the thickness of the nth layer

P $= \text{diag}(p_1, p_2, p_3)$

P' $= \text{diag}(p_4, p_5, p_6)$

A $= (a_1, a_2, a_3)$

A' $= (a_4, a_5, a_6)$

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Table 1. Structural models used for the calculations.

Model No.	Layer No.	Vp (km/sec)	Vs (km/sec)	Density (gm/cc)	Thickness (km)
1	1	transversely isotropic medium (Table 2)		3.3	35.0
	2 -	8.12	4.7	3.3	half-space
2	1	7.25	4.2	2.9	30.0
	2	(001)-cut olivine (Table 2)		3.324	30.0
	3	10.0	5.7	3.6	half-space

Table 2. (a) Elastic constants of a transversely isotropic medium.

$$A = 196.0 \quad C = 244.0 \quad F = 70.0 \quad L = 82.5 \quad N = 67.0 \times 10^9 \text{ N·m}^{-2}$$

(b) Elastic constants of orthorhombic olivine.

$$c_{1111} = 324.0 \qquad c_{2222} = 198.0 \qquad c_{3333} = 249.0 \times 10^9 \text{ N·m}^{-2}$$
$$c_{1122} = 59.0 \qquad c_{2233} = 78.0 \qquad c_{3311} = 79.0$$
$$c_{1212} = 79.3 \qquad c_{2323} = 66.7 \qquad c_{1313} = 81.0$$
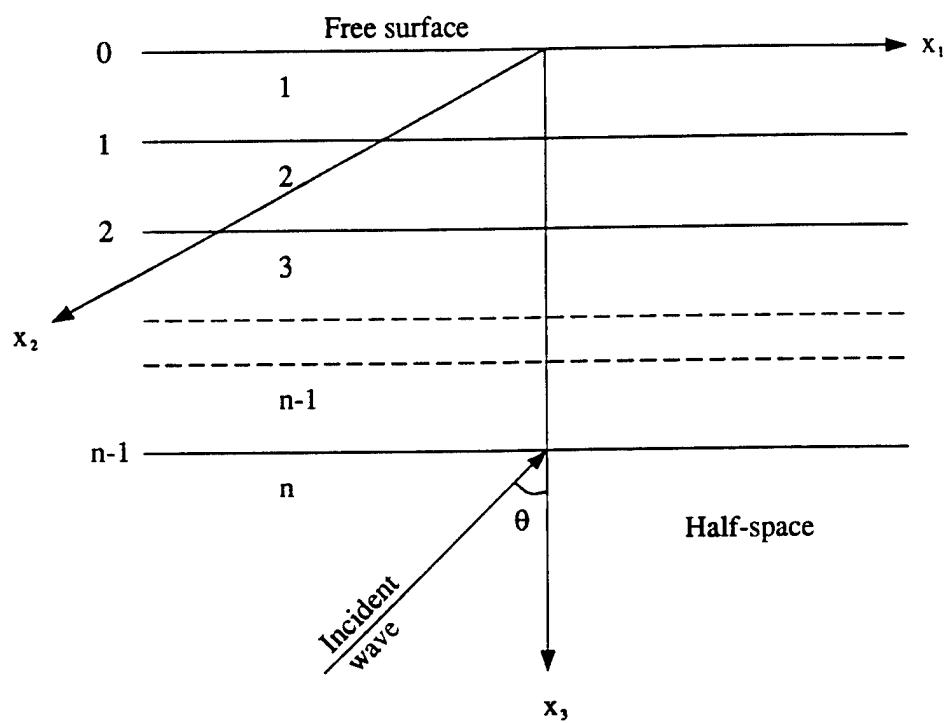
Figure 1. Coordinate axes for multilayered models where the layers can be isotropic or anisotropic. θ is the angle of incidence.
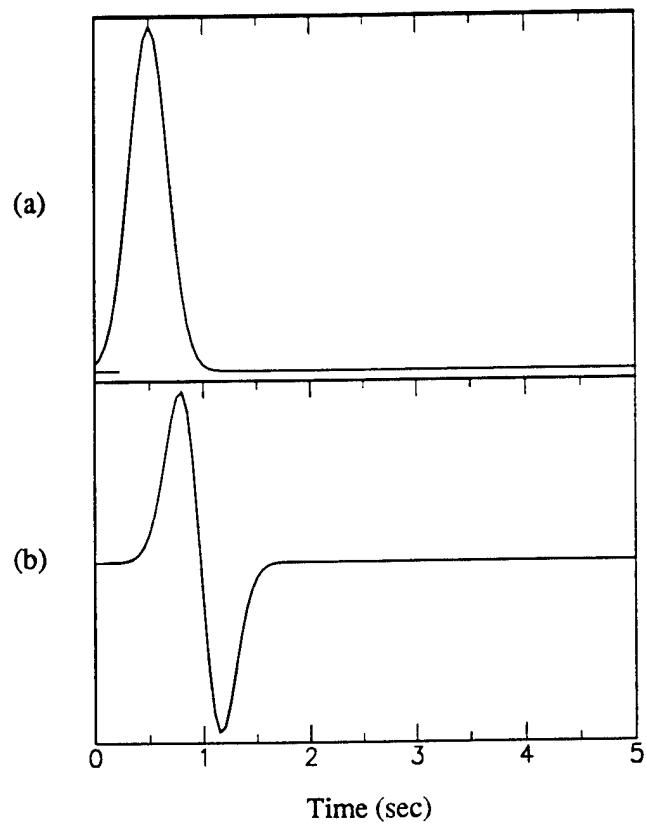
Figure 2. The input pulses for the synthetic seismograms presented here.
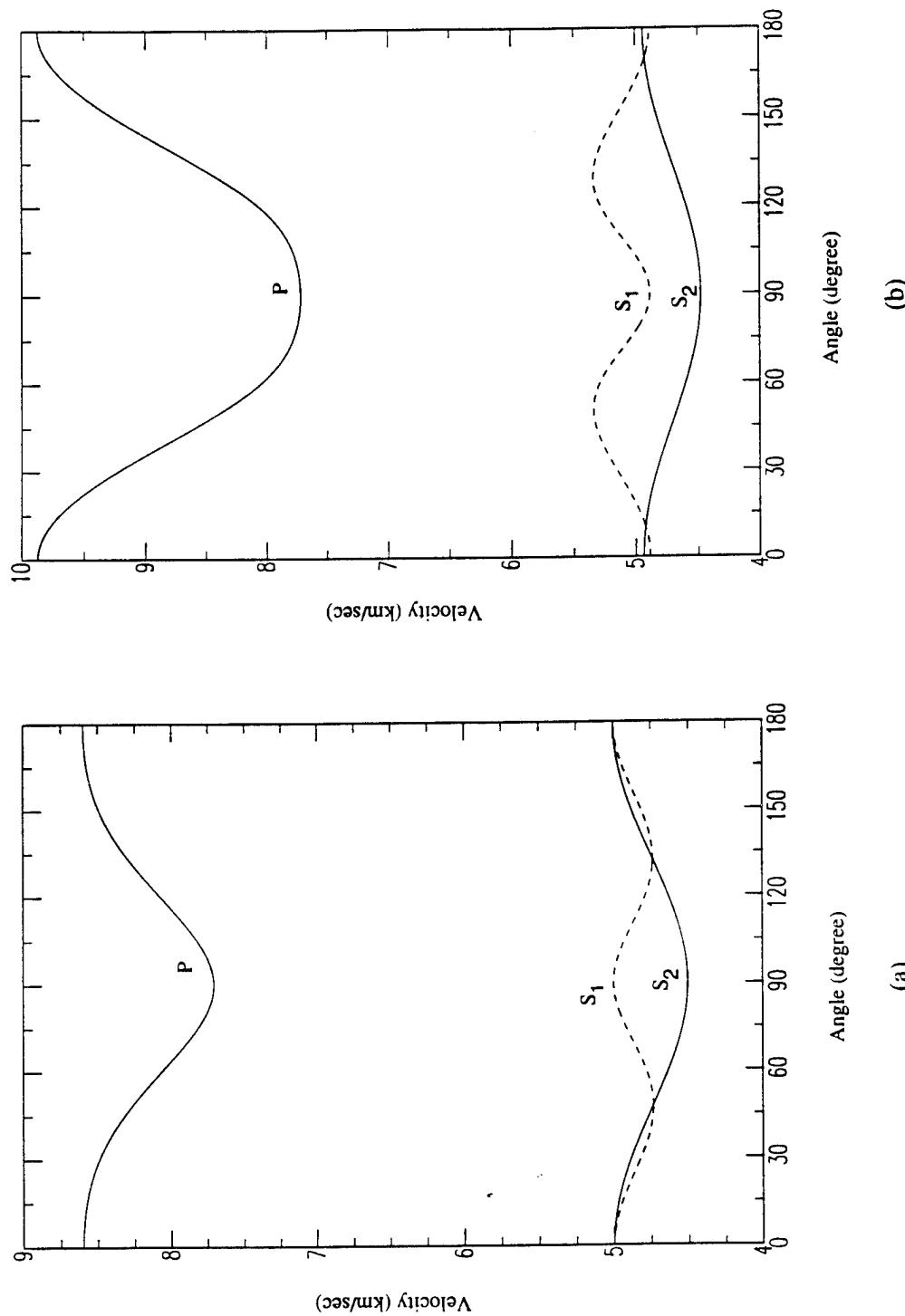
Figure 3. Variations of body wave velocities for propagation in orthogonal planes of anisotropic medium (a) in the model 1 of Table 1 and (b) in the model 2 of Table 1. The angle of the direction is reckoned from the axis of symmetry.

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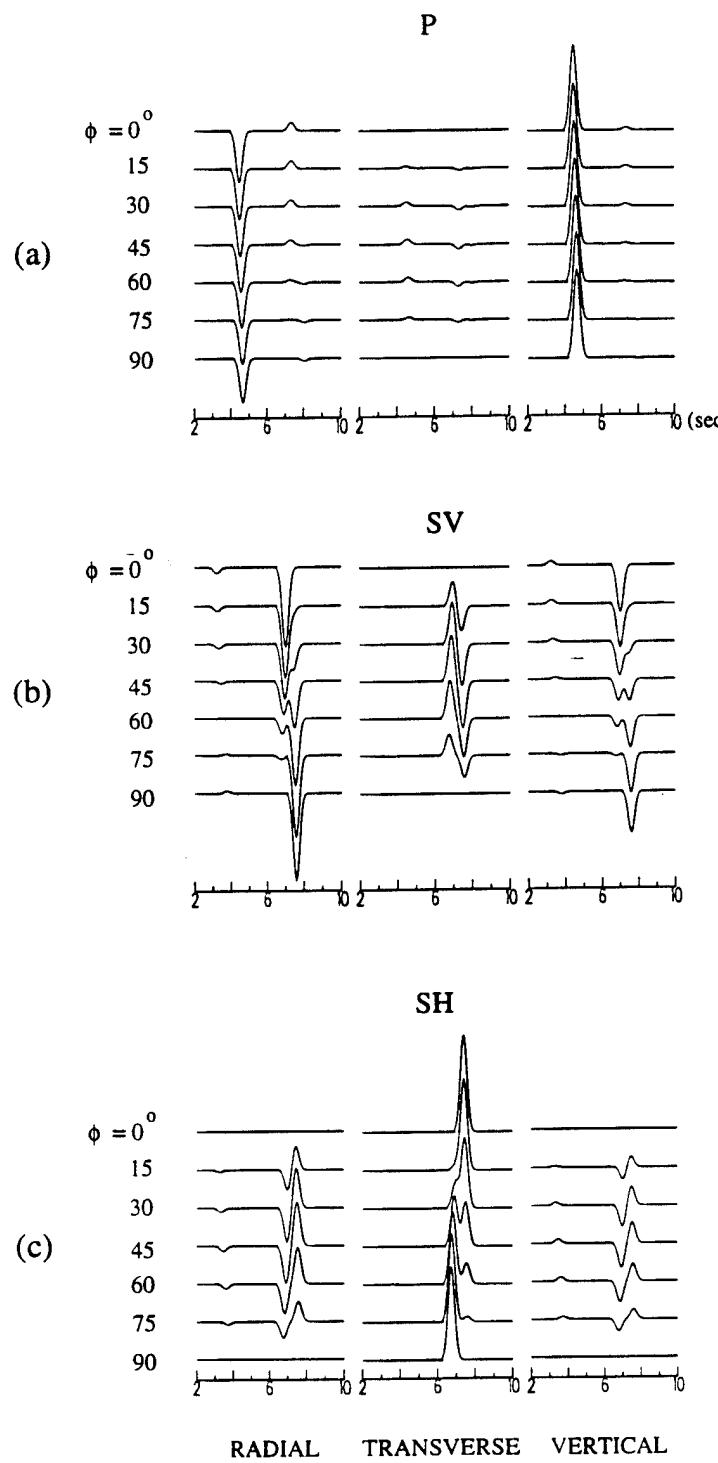
Figure 4. Displacements of the free surface produced by (a) P, (b) SV, (c) SH at 25° angle of incidence on transversely isotropic layer in Model 1 of Table 1. φ is angle between the axis of symmetry of the transversely isotropic layer and the horizontal projection of the wave propagation direction. The input pulse used here is given by figure 1(a).
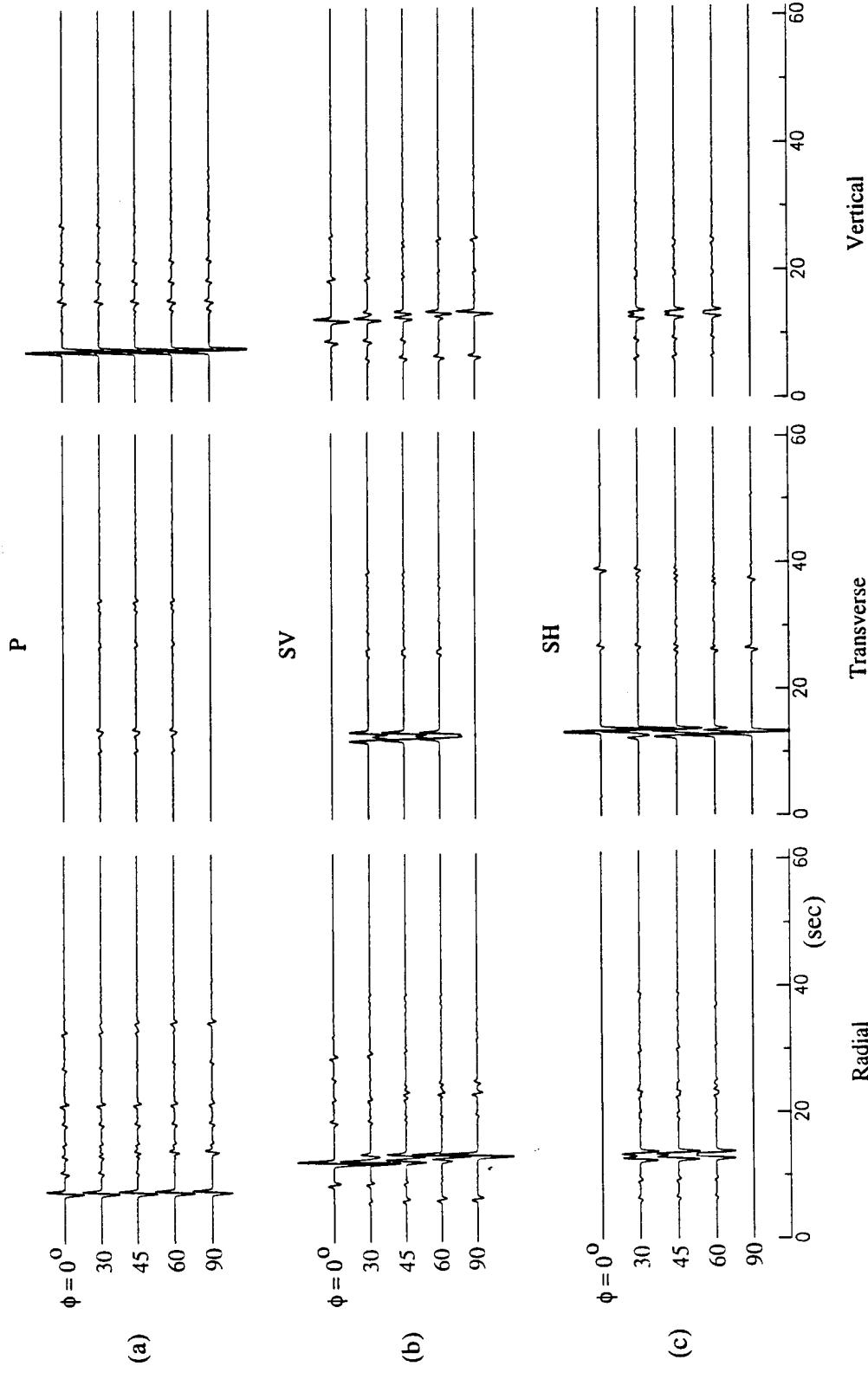
Figure 5. Displacements of the free surface produced by (a) P, (b) SV, (c) SH at 35° angle of incidence on (001)-cut olivine in Model 2 of Table 1. φ is the angle measured from (100) towards (010). The input pulse used here is given by figure 1(b).

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TELEDB

A Teleseismic Database and Moment Tensor Inversion System

Tutorial

for the
IRIS Short Course on Moment Tensor Inversion
December 15 - 16, 1995

by

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Introduction

The purpose of this tutorial is to provide some documentation of the codes in the TELEDB system so a reasonably proficient seismology graduate student can quickly perform moment tensor inversions using IRIS waveform data. I had high hopes of integrating my synthetic waveform and inversion codes with the JSPC software package DATASCOPE, a fine database system written by Dan Quinlan at the JSPC. As it turned out, because of the amount of work that I put into rewriting the teleseismic waveform program, TELEDB falls far short of utilizing the full range of utilities and formats that is in DATASCOPE. The current version of the software incorporates some very useful DATASCOPE utilities for building database files from IRIS SAC files. I tried to preserve the integrity of the CSS3.0 database schema, but as time pressed for completing programming for this short course, I had to "bend" it quite a bit by making up new file formats to interface with various waveform utilities, the synthetics code, and the inversion code. Although I would like to more fully integrate this package with DATASCOPE, perhaps some enterprising graduate student might be better inclined and more proficient at programming than me to do so.

Aside from several DATASCOPE modules, my style of programming consists of patching together several FORTRAN 77 programs through a UNIX C shell script. Most scripts set up a small parameter file that is then used by one or more fortran programs that then access database files and waveform files. Use of SAC (Seismic Analysis Code, Lawrence Livermore Laboratory) occurs often in these scripts and the data are assumed to reside in SAC binary files. A particular directory structure is assumed by these scripts and must be set up by the user using a utility script. I am sure there are more elegant ways of programming, but I have always been attracted to the simple and the direct, knowing how easy it is to make mistakes.

Before getting into the details of the software system, the next section outlines theory for computations of the Green's functions for teleseismic body waves and the waveform inversion.

Computation of Teleseismic Body Waves

Accurate moment tensor inversion of seismic waveforms requires that the Green's functions be known. This is actually the hardest part of all seismological problems since knowledge of earth structure is often very sketchy. Fortunately, teleseismic body waves can be explained with fairly simple theory. Rays from a buried source interact with structure near the source but then are largely unaffected by propagation through the lower mantle until arriving at the receiver. Receiver effects for vertical P waves

and tangential S waves are relatively minor and do little to mask the signal controlled mostly by source radiation pattern and near-source structure.

A FORTRAN 77 program called **dishask** (I will use bold characters for modules in TELEDB) performs the computations for the problem outlined in Figure 1. The far-field response of a point source in plane layered media is calculated using the Thomson-Haskell technique. The phase term for propagation and geometrical spreading in the halfspace is replaced by the geometrical spreading effect of a P or S wave propagating through a reference spherical earth structure. The far-field source response is then input at the receiver side as a plane wave incident under a plane layered receiver structure. The program allows for differing source and receiver structures. The source structure may include a surface water layer for modeling events under oceans. Receiver structures are allowed to be different since stations are situated in many different tectonic environments and typical structures can have significant effects on the resulting response, depending on displacement component. The TELEDB database structure is setup so that as knowledge of structure under various receivers becomes available, these structure models can then be incorporated in future calculations.

Following the notation of Harkrider (1964; 1970) the downgoing P and SV wave potential coefficients are given by the following matrix equations. Geometry for the source problem is shown in Figure 2.

$$
\begin{bmatrix} \hat{\Delta}'_n \\ \hat{\Delta}'_n \\ \hat{\omega}'_n \\ \hat{\omega}'_n \end{bmatrix} = \mathbf{J}_R \left\{ \begin{bmatrix} \dfrac{\dot{u}_{R_0}}{c} \\ \dfrac{\dot{w}_{R_0}}{c} \\ \sigma_{R_0} \\ 0 \end{bmatrix} + \mathbf{A}_{R_{S1}}^{-1} \begin{bmatrix} \delta\left(\dfrac{\dot{u}_{R_s}}{c}\right) \\ \delta\left(\dfrac{\dot{w}_{R_s}}{c}\right) \\ \delta\sigma_{R_s} \\ \delta\tau_{R_s} \end{bmatrix} \right\}
\tag{1}
$$

where,

$$
\mathbf{J}_R = \mathbf{E}_R^{-1} \mathbf{A}_R
\tag{2}
$$

SOURCE STRUCTURE

RECEIVER STRUCTURE

Thomson Haskell

Thomson Haskell

r

* Point Source

z

FLAT EARTH TRANSFORMATION
OF SPHERICAL EARTH MODEL

GEOMETRICAL
RAY THEORY, Q
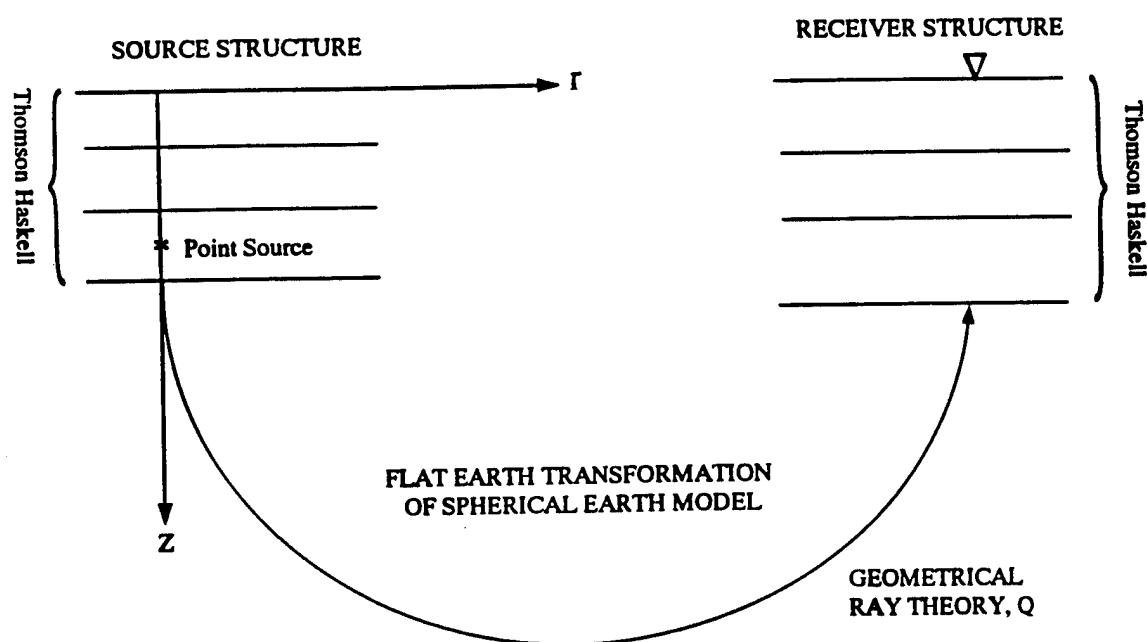
Figure 1

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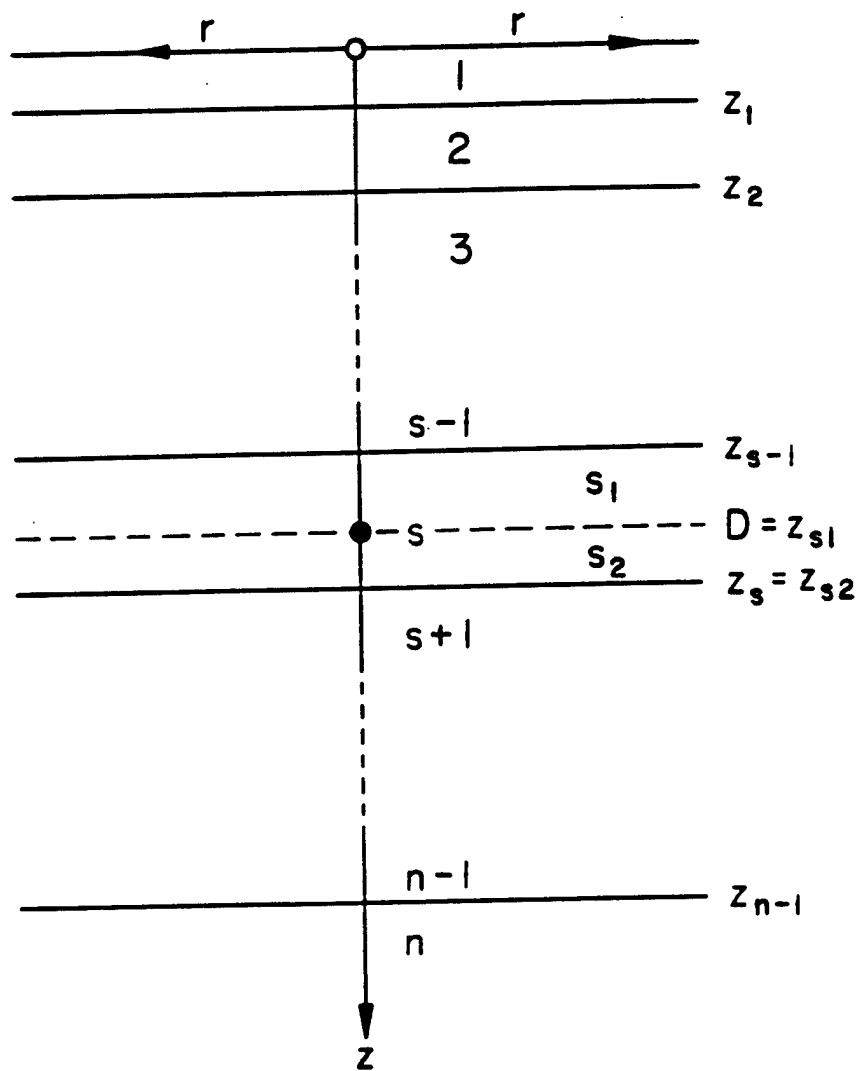
Figure 2

$$A_R = a_{R_{n-1}} a_{R_{n-2}} \cdots a_{R_1} \qquad (3)$$

$$A_{R_{S1}} = a_{R_{S1}} a_{R_{S-1}} \cdots a_{R_1} \qquad (4)$$

$$\delta() = \text{source jump conditions}$$

and a_{Ri} is the Haskell layer matrix.

At the free surface

$$\sigma_{R_0} = 0 . \qquad (5)$$

For a water layer on top of the layered stack with a thickness of d_0

$$\frac{\dot{w}_o}{c} = A_{f_{11}} \frac{\dot{w}(-d_0)}{c} \qquad (6)$$

$$\sigma_{R_0} = A_{f_{21}} \frac{\dot{w}(-d_0)}{c} . \qquad (7)$$

Af is the Haskell layer matrix for a fluid.

The equations for the downgoing SH wave potential are given by

$$\begin{bmatrix} \hat{\varepsilon}'_n \\ \hat{\varepsilon}'_n \end{bmatrix} = \mathbf{J}_L \left\{ \begin{bmatrix} \dfrac{\dot{v}_{L_0}}{c} \\ 0 \end{bmatrix} + \mathbf{A}_{L_{S1}}^{-1} \begin{bmatrix} \delta\left(\dfrac{\dot{v}_{L_s}}{c}\right) \\ \delta\tau_{L_s} \end{bmatrix} \right\} \qquad (8)$$

where $\mathbf{J_L}$ and $\mathbf{A_L}^{-1}$ are defined in an analogous way to the P-SV system above.

The source jump conditions are given by:

$$\delta\left(\frac{\dot{u}_{R_s}}{c}\right) = k^2 \left[\left(S_{01}^+ - S_{01}^- \right) - ikr_{\beta_s} \left(S_{02}^+ + S_{02}^- \right) \right] \qquad (9)$$

$$\delta\left(\frac{\dot{w}_{R_s}}{c}\right) = ik\left[-ikr_{\alpha_s}\left(S_{01}^+ + S_{01}^-\right) + k^2\left(S_{02}^+ - S_{02}^-\right)\right] \quad (10)$$

$$\delta\sigma_{R_s} = k^2 c^2 \rho_S\left[\left(\gamma_S - 1\right)\left(S_{01}^+ - S_{01}^-\right) - ikr_{\beta_s}\gamma_S\left(S_{02}^+ + S_{02}^-\right)\right] \quad (11)$$

$$\delta\tau_{R_s} = k^2 c^2 \rho_S\left[-\gamma_S r_{\alpha_s}\left(S_{01}^+ + S_{01}^-\right) - ik\left(\gamma_S - 1\right)\left(S_{02}^+ - S_{02}^-\right)\right] \quad (12)$$

$$\delta\left(\frac{\dot{v}_{L_s}}{c}\right) = ik^2\left(S_{03}^+ - S_{03}^-\right) \quad (13)$$

$$\delta\tau_{L_s} = -ik^2\mu_S r_{\beta_s}\left(S_{03}^+ + S_{03}^-\right) \quad (14)$$

where,

$$k = \frac{\omega}{c} \quad (15)$$

$$r_v = \left(\frac{c^2}{v^2} - 1\right)^{\frac{1}{2}} \quad (16)$$

$$\gamma = 2\left(\frac{\beta_S}{c}\right)^2. \quad (17)$$

The source coefficients $S_{01}^\pm$, etc., are given by

Vertical Strike-Slip:

$$S_{01}^+ = S_{01}^- = \frac{Kk^2 i}{r_\alpha} \quad (18)$$

$$S_{02}^+ = -S_{02}^- = -Kk \quad (19)$$

$$S_{03}^+ = S_{03}^- = -\frac{Kk_\beta^2 i}{r_\beta} \qquad (20)$$

Vertical Dip-Slip

$$S_{01}^+ = -S_{01}^- = 2Kk^2 \qquad (21)$$

$$S_{02}^+ = S_{02}^- = \frac{Ki(k_\beta^2 - 2k^2)}{kr_\beta} \qquad (22)$$

$$S_{03}^+ = -S_{03}^- = -Kk_\beta^2 \qquad (23)$$

Compensated Linear Vector Dipole (CLVD)

$$S_{01}^+ = S_{01}^- = -\frac{Ki(2k_\alpha^2 - 3k^2)}{r_\alpha} \qquad (24)$$

$$S_{02}^+ = -S_{02}^- = -3Kk \qquad (25)$$

$$S_{03}^+ = S_{03}^- = 0 \qquad (26)$$

Isotropic Source (Implosion)

$$S_{01}^+ = S_{01}^- = \frac{Ki\omega^2}{\alpha^2 r_\alpha} \qquad (27)$$

$$S_{02}^+ = S_{02}^- = 0 \qquad (28)$$

$$S_{03}^+ = S_{03}^- = 0 \qquad (29)$$

where,

$$K = -\frac{\mu L H \hat{D}(\omega)}{4\pi\rho\omega^2} \qquad (30)$$

$$k_\alpha = \frac{\omega}{\alpha} \qquad (31)$$

$$k_\beta = \frac{\omega}{\beta}. \qquad (32)$$

Spectral displacements in the halfspace are given by

$$\hat{U}_P = \frac{r_{\alpha_n}}{k_{\alpha_n}} i^{l+2} \hat{\Delta}'_n \frac{e^{-ik_{\alpha_n}R}}{R} \qquad (33)$$

$$\hat{U}_{SV} = \frac{2r_{\beta_n}}{k_{\beta_n}} i^{l+2} \hat{\omega}'_n \frac{e^{-ik_{\beta_n}R}}{R} \qquad (34)$$

$$\hat{U}_{SH} = r_{\beta_n} i^{l+2} \hat{\varepsilon}'_n \frac{e^{-ik_{\beta_n}R}}{R} \qquad (35)$$

$$l = 2 \quad \text{for vertical strike-slip}$$

$$= 1 \quad \text{for vertical dip-slip}$$

$$= 0 \quad \text{for CLVD and isotropic sources.}$$

Solution of the matrix equations give the downgoing wave coefficients:

$$\hat{\Delta}'_n = \frac{1}{\det J_R}[A + B + C + D] \qquad (36)$$

$$\hat{\omega}'_n = \frac{1}{\det J_R}[E + F + G + K] \qquad (37)$$

$$\hat{\varepsilon}'_n = \frac{H_{L_{11}} J_{L_{21}} - H_{L_{21}} J_{L_{11}}}{J_{L_{21}} - J_{L_{11}}} \qquad (38)$$

where

$$\mathbf{H}_R = \mathbf{J}_R \mathbf{A}_{R_{S1}}^{-1} \begin{bmatrix} \delta\left(\dfrac{\dot{u}_{R_s}}{c}\right) \\[2ex] \delta\left(\dfrac{\dot{w}_{R_s}}{c}\right) \\[2ex] \delta\sigma_{R_s} \\[2ex] \delta\tau_{R_s} \end{bmatrix} \qquad (39)$$

$$\mathbf{H}_L = \mathbf{J}_L \mathbf{A}_{L_{S1}}^{-1} \begin{bmatrix} \delta\left(\dfrac{\dot{v}_{L_s}}{c}\right) \\[2ex] \delta\tau_{L_s} \end{bmatrix} \qquad (40)$$

$$A = H_{R_{11}} \left\{ \left(J_{R_{42}} - J_{R_{32}}\right) J_{R_{21}} - \left(J_{R_{41}} - J_{R_{31}}\right) J_{R_{22}} \right\} \qquad (41)$$

$$B = H_{R_{21}} \left\{ \left(J_{R_{41}} - J_{R_{31}}\right) J_{R_{12}} - \left(J_{R_{42}} - J_{R_{32}}\right) J_{R_{11}} \right\} \qquad (42)$$

$$C = H_{R_{31}} \left\{ J_{R_{21}} J_{R_{12}} - J_{R_{22}} J_{R_{11}} \right\} \qquad (43)$$

$$D = H_{R_{41}} \left\{ J_{R_{22}} J_{R_{11}} - J_{R_{21}} J_{R_{12}} \right\} \qquad (44)$$

$$E = H_{R_{11}} \left\{ J_{R_{42}} J_{R_{31}} - J_{R_{41}} J_{R_{32}} \right\} \qquad (45)$$

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$$F = H_{R_{21}} \left\{ J_{R_{41}} J_{R_{32}} - J_{R_{42}} J_{R_{31}} \right\} \qquad (46)$$

$$G = H_{R_{31}} \left\{ \left(J_{R_{21}} - J_{R_{11}} \right) J_{R_{42}} - \left(J_{R_{22}} - J_{R_{12}} \right) J_{R_{41}} \right\} \qquad (47)$$

$$K = H_{R_{41}} \left\{ \left(J_{R_{22}} - J_{R_{12}} \right) J_{R_{31}} - \left(J_{R_{21}} - J_{R_{11}} \right) J_{R_{32}} \right\} \qquad (48)$$

$$\det J_R = \left(J_{R_{42}} - J_{R_{32}} \right) \left(J_{R_{21}} - J_{R_{11}} \right) - \left(J_{R_{41}} - J_{R_{31}} \right) \left(J_{R_{22}} - J_{R_{12}} \right) \qquad (49)$$

All of these quantities can be explicitly found in the dishask source code.

Geometrical spreading is calculated for a flattened spherical earth model using the following equation.

$$a_0^2 = \frac{\rho_1 v_1^2}{\rho_0 v_0^2} \frac{1}{x} \frac{p}{\eta_{v_0} \eta_{v_1}} \left(-\frac{dp}{dx} \right) \left(\frac{\theta}{\sin \theta} \right) \qquad (50)$$

where,

ρ_1 = density of mantle at source

ρ_0 = density of mantle at receiver

v_0 = wave velocity at source

v_1 = mantle wave velocity at receiver

x = distance

p = ray parameter

θ = spherical earth distance (radians)

$$\eta_{v_i} = \left(\frac{1}{v_i^2} - p^2 \right)^{\frac{1}{2}} \quad .$$

a_0 is the amplitude of the P or S wave in the receiver mantle directly below the layered structure. There is a series of subroutines in dishask to determine the appropriate ray parameter and geometrical spreading given a source-receiver distance.

Finally, the receiver effect is computed using the Thomson-Haskell method for an incident plane wave under a plane layered structure. The free surface displacements are given by:

$$u_P = \frac{2c}{\alpha_n} \frac{\left(J_{R_{42}} - J_{R_{32}}\right)}{\det J_R} \qquad (51)$$

$$w_P = \frac{2c}{\alpha_n} \frac{\left(J_{R_{41}} - J_{R_{31}}\right)}{\det J_R} \qquad (52)$$

$$u_{SV} = \frac{c}{\beta_n} \frac{\left(J_{R_{12}} - J_{R_{22}}\right)}{\det J_R} \qquad (53)$$

$$w_{SV} = \frac{c}{\beta_n} \frac{\left(J_{R_{41}} - J_{R_{11}}\right)}{\det J_R} \qquad (54)$$

$$v_{SH} = \frac{2\rho_n \beta_n^2 r_{\beta_n}}{\rho_n \beta_n^2 r_{\beta_n} A_{L_{11}} + A_{L_{21}}} \qquad (55)$$

where, w, u, v are vertical, radial and tangential displacements, respectively. The notation for the layered receiver structure follows the same conventions as the source problem and Figure 2, except, obviously, there are no source layers.

Complex spectra for the 4 Green's functions are computed and multiplied with the spectra for the appropriate receiver response and the geometrical spreading factor. An inverse FFT brings the spectra into the time domain.

There is one additional detail which may be useful to researchers. Attenuation is included in both source and receiver structures through the use of complex wave velocity. "Effective velocity", veff, is given by:

$$\frac{1}{v_{eff}} = \frac{1}{v}\left(1 - \frac{1}{\pi Q}\log\left[\frac{\gamma\omega}{\omega_0}\right] - \frac{i}{2Q}\right) \qquad (56)$$

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where v is P or S wave velocity and Q, P or S wave Q. ω_0 is an arbitrary attenuation band cutoff frequency (set here to a period of 1000 sec) and γ, Euler's number. This form of complex velocity uses Futterman's (1962) result for phase. Attenuation due to wave propagation in the mantle also uses the Futterman operator and is included in the final spectral multiplication.

The source time function is parameterized by a series of triangular elements and is discussed in the next section. I originally used boxcar elements in past inversions but Nabelek's (1982) triangular element parameterization is more appealing since it produces a smoother time function.

Inversion of Teleseismic Body Waves

The inversion for moment tensor and time function follows Wiggin's(1972) method of Singular Value Decomposition and singular value truncation for damping. Because joint inversion of both sets of parameters is nonlinear, I discuss the details of the source parameterization in addition to those in the shortcourse tutorial on moment tensors.

Displacements can be written in terms of the moment tensor

$$u_i(\bar{x},t) = G_{ij,k}\left[M_{jk}(\bar{x}',t')\right] \qquad (57)$$

where

$$M_{ij}(\bar{x}',t') = M_{ji}(\bar{x}',t') \qquad (58)$$

are the moment tensor elements, and $G_{ij,k}$ are the Green's functions. In a cylindrical coordinate system, and for a deviatoric moment tensor source

$$w(t,r,z,Az) = s(t) * \sum_{i=1}^{3} \tilde{H}_{w_i}(t,r,z) A_i'(\theta,\lambda,\delta) \qquad (59)$$

$$q(t,r,z,Az) = s(t) * \sum_{i=1}^{3} \tilde{H}_{q_i}(t,r,z) A_i'(\theta,\lambda,\delta) \qquad (60)$$

$$v(t,r,z,Az)=s(t)*\sum_{i=1}^{2}\tilde{H}_{v_i}(t,r,z)A'_{i+3}(\theta,\lambda,\delta) \quad (61)$$

or,

$$w(t,r,z,Az)=s(t)*\sum_{i=1}^{5}\tilde{H}'_{w_i}(t,r,z)M'_{i} \quad (62)$$

where

$$M'_1=M_{11}$$
$$M'_2=M_{22}$$
$$M'_3=M_{12} \quad (63)$$
$$M'_4=M_{13}$$
$$M'_5=M_{23}$$

and

$$\tilde{H}'_{w_1}=-\frac{1}{2}\tilde{H}_{w_1}\cos(2Az)+\frac{1}{2}\tilde{H}_{w_2}$$
$$\tilde{H}'_{w_2}=\frac{1}{2}\tilde{H}_{w_1}\cos(2Az)+\frac{1}{2}\tilde{H}_{w_3}$$
$$\tilde{H}'_{w_3}=-\tilde{H}_{w_1}\sin(2Az) \quad (64)$$
$$\tilde{H}'_{w_4}=\tilde{H}_{w_2}\cos(Az)$$
$$\tilde{H}'_{w_5}=\tilde{H}_{w_2}\sin(Az)$$

The Green's functions, e.g., H_{w_i}, are given above for a vertical strike-slip source (i=1), vertical dip-slip source (i=2), and CLVD source (i=3).

The source time function parameterized by

$$s(t)=\sum_{k=1}^{L}s_k B(t-\tau_k) \quad (65)$$

where $B(t - \tau_k)$ is a triangular element characterized by equal rise times and fall-off times and a width of $\Delta\tau$.

$$\tau_k = \frac{1}{2}\Delta\tau(k - 1) \qquad (66)$$

The far-field time function is normalized such that

$$\frac{\Delta\tau}{2}\sum_{k=1}^{n} s_k = 1 \qquad (67)$$

Then,

$$w(t,r,z,Az)=[\sum_{k=1}^{L} s_k B(t - \tau_k)]*\sum_{i=1}^{5} \tilde{H}'_{w_i}(t,r,z,Az)M'_i \qquad (68)$$

or

$$w(t,r,z,Az)=\sum_{k=1}^{L}\sum_{i=1}^{5} s_k M'_i[B(t - \tau_k)* \tilde{H}'_{w_i}(t,r,z,Az)] \qquad (69)$$

The object of the inversion is to find the moment tensor and time function coefficients. Since the equation shows a direct tradeoff between moment tensor and time function, an equation of constraint is added to the final matrix equations before inversion. This equation states that the time function perturbations average to zero so that the time function remains normalized:

$$\sum_{k=1}^{n} \Delta s_k = 0 \qquad (70)$$

The matrix equation are set up in a standard way

$$\Delta C_j = O_j - C_j^0 = \sum_{i=1}^{n} \frac{\partial C_j}{\partial P_i}\Delta P_i = A_{ij}\Delta P_i \qquad (71)$$

where

$$O_j = \text{observed ground motion at time } j$$

$$C_j^0 = \text{starting model synthetic at time } j \qquad (72)$$

$$\Delta P_i = \text{parameter perturbation}$$

$$A_{ij} = \left.\frac{\partial C_j}{\partial P_i}\right|_{\mathbf{P}^0}$$

Weighting matrices are also included where, $\mathbf{W}$ is the parameter weighting matrix and $\mathbf{S}$ is the data covariance matrix

$$S_{ij} = \text{cov}\left(O_i O_j\right) \qquad (73)$$

I assume

$$S_{ii} = \sigma_i^2 \qquad (74)$$

The transformed system of equations become

$$\mathbf{A}' \Delta \mathbf{P}' = \Delta \mathbf{C}' \qquad (75)$$

where

$$\mathbf{A}' = \mathbf{S}^{-1/2} \mathbf{A} \mathbf{W}^{1/2}$$

$$\Delta \mathbf{P}' = \mathbf{W}^{-1/2} \Delta \mathbf{P} \qquad (76)$$

$$\Delta \mathbf{C}' = \mathbf{S}^{-1/2} \Delta \mathbf{C} \ .$$

Using Singular Value Decomposition

$$\mathbf{A}' = \mathbf{U}\Lambda\mathbf{V}^T \qquad (77)$$

$$\Delta\mathbf{P}' = \mathbf{V}\Lambda^{-1}\mathbf{U}^T\Delta\mathbf{C}' \qquad (78)$$

The variance of the solution is examined to determine if there are any near-zero singular values which would indicate and unstable inverse. An arbitrary cut-off threshold is specified to cut off these small singular values which damps the inverse solution. Since small singular values are usually associated with the time function parameterization, another equation of constraint can be included in the system of equations prior to inversion. which specifies that everyother time function element is inverted with the element between being specified by the average of the adjacent elements. This averaging technique reduces the number of independent variables and helps convergence sometimes. Note that you must specify an odd number of time function elements to perform the averaging.

Singular value decomposition allows a number of useful secondary results to be calculated during the inversion. Data importance is evaluated by summing along the columns of the information density matrix for the seismogram of a particular station. The information density matrix, or data resolution matrix is given by $\mathbf{U}^T\,\mathbf{U}$. The parameter resolution matrix $\mathbf{V}^T\,\mathbf{V}$ is also useful to examine for the tradeoff between parameters. If all singular values are kept, this matrix is the identity matrix and all parameters are perfectly (in linear theory) resolved, aside from errors induced by noise in the data.

The success of the inversion is examined several ways. One is to simply see how good the data waveforms have been fit. This measure is calculated by;

$$\sigma_{RMS} = \left(\frac{1}{N}\sum_{i=1}^{N} [O_i - C_i]^2 \right)^{\frac{1}{2}} \qquad (79)$$

The least-squares error is also calculated to examine how good the inverse approximated the data perturbations:

$$|\mathbf{A}\Delta\mathbf{P} - \Delta\mathbf{C}| \qquad (80)$$

In addition to these formal error criteria, the source model is decomposed into the major double couple and a remainder CLVD source.

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The amount of non-double couple source can be interpreted as a measure of misfit, if you believe that earthquake sources must conform to the double couple or dislocation model.

In practice, it is efficient to first perform a linear moment tensor inversion, assuming a source time function and source depth, to get a reasonable starting model for the source radiation pattern. Once an approximate moment tensor has been found, joint inversion for time function and moment tensor is performed since this is a non-linear process. Several interations may be needed for convergence, if it occurs. The best depth is chosen by examining the three error criteria and minimizing all, if possible.

The TELEDB System

Overview

The TELEDB software tools have been designed for the formidable problem of downloading large amounts of IRIS waveform data from the SPYDER system in SAC binary format , preparing the data for moment tensor inversion, and then inverting the data. The waveform data are interogated using DATASCOPE software to produce database files, and these files are used in subsequent processing steps.

The large number of waveform files available for any one event is a boon for science but makes the data processing extremely tedious unless big pieces of the processing can be automated. The approach used here is to make use of database files to keep track of the data and data processing and to standardize the file system so that scripts can be used over and over for different earthquake events.

File Structure

A basic UNIX directory structure is assumed. Assume that you are working on an earthquake from the Yunnan province in China. The root event directory may be called "yunnan" with various subdirectories created underneath this root.

./yunnan	root directory
./yunnan/data	root data directory
./yunnan/data/raw	raw data

./yunnan/data/process	processed data of several types
./yunnan/data/invert	final windowed and time shifted waveform data
./yunnan/sacplz	SAC polezero files
./yunnan/synth	An extra directory for placing synthetic seismograms
./yunnan/greens	inversion Green's functions
./yunnan/invert	inversion results
./yunnan/db	database files

./yunnan may be a subdirectory under "teledb" which contains the executables, source code, earth models, and SEED response files:

teledb

teledb/bin	Shell scripts and binaries
teledb/src	source code
teledb/emodels	earth model files
teledb/responses	SEED instrument response files downloaded from IRIS

Most all scripts require that a UNIX environmental variable called $PSUMOM be set in your login or .cshrc file. For example, if the teledb directory is under /tremor/s0/cal, then:

setenv PSUMOM /tremor/s0/cal/teledb

After setting PSUMOM, an event directory with subdirectories can be built by invoking the C Shell **Create_directory.csh** which is self-explanatory. (See the Appendix for C Shell script listings.)

Making a Database

After the basic directory structure has been set up, obtain data from IRIS. The system was developed around the practical problem of downloading data from the SPYDER system over INTERNET. Log into the SPYDER system, choose an event, and download SAC binary data into the /data/raw subdirectory.

After the data have been obtained, make sure there are no other files in the "/data/raw" directory so database files may be built using the **sac2db** command. If you want database tables named with the root "yunnan", for example, you would type, in the directory:

<p align="center">sac2db * yunnan</p>

This program finds all the files in the directory and builds a CSS3.0 database. Move the database files to the "/db" directory. At this point you will need to make a good origin file, since **sac2db** will have made one that contains a lot of garbage because IRIS SAC files do not contain all of the necessary information. This can be done using the DATASCOPE utility **dbe**. In the "/db" directory type, for example:

<p align="center">dbe yunnan</p>

Get up the menu and make a new origin table. Save it.

Instrument Corrections

Now that the necessary database tables have been made, notably, "event.wfdisc" and "event.origin", the data can be processed for inversion. This consists of the following steps:

1. Calculate P and S wave arrival times for phase interpretation. Put these times into the data file.
2. Construct a SAC polezero file for a particular data trace.
3. Write a SAC macro file for instrument correction.

4. Correct the data for instrument response and make
ground displacements.

These functions are contained in the C Shell **prewave.csh**. A reading of this script shows that it builds an input file for a Fortran 77 program called **prewave** that interogates the database files and SAC data files for appropriate information. **prewave** creates another C Shell which generates SAC polezero files from the SEED responses contained in teledb/responses using the program **evalresp**, which was obtained from the IRIS ftp archives. Note that **prewave** looks for an appropriate response file, but if it cannot find one, it will discard the particular data waveform from consideration. It is the job of the analyst to make sure that SEED response files for each waveform channel are available in the "teledb/responses" directory. These are available from a SEED tape volume if the data are obtained that way. I am providing the most recent set of responses available from the IRIS ftp archives.

All of the C Shell scripts are fairly self-explanatory if they are invoked without arguments.

The **prewave.csh** script will also make a set of new database files, notably newdb.wfdisc which contain all of the information needed on data waveforms that have been corrected for instrument response. The corrected data will also be written to the "/data/process" directory for further processing.

Vector Rotation

The next step in processing is to rotate the horizontal waveforms into the theoretical backazimuth to the event, to produce SV and SH motions. This is done using **rotate.csh**. This C Shell builds a simple input file for the **rotate** program. **rotate** then interogates the database .wfdisc file to build a SAC macro file for the vector rotation. SAC is then invoked to do the actual work. New database files are produced after this step, also.

Analyst Decisions

Until now, the data processing has been routine with little analyst interaction, but this is the appropriate point to really examine the data to see if there is anything worthwhile studying! Use SAC and look and P and SH wave data. How is the signal-to-noise ratio? What kind of high pass filter will remove baseline and long period noise problems? Which stations will give useful data? Can you see P arrivals, S arrivals based on the travel time estimates? (P and S times will be marked by SAC T1 and T2 markers.)

Choose your data wisely and jot down the channels and stations that you want to further consider.

Another C Shell script is invoked to create the next database table, which I call a ".stachan table", that will be used in synthetic seismogram calculations and in the moment tensor inversion. This is where I diverge from DATASCOPE CSS3.0 conventions. The ".stachan" file can be considered to be a parameter file in the DATASCOPE scheme of things. The C Shell is called **create_stachan.csh** and is a bit tedious since it interactively asks you questions about your data. Again, it constructs a simple data file which is read by a fortran program called **sctable**, which actually does the asking. A future improvement would be to use DATASCOPE itself to create the table, but that entails modifying the CSS3.0 schema. The ".stachan" file is a basic data file containing information about each waveform channel of interest.

Data Windowing and Decimation

Next, I recommend that the final data be windowed for use in the inversion program. The inversion program **momvert** only allows data array lengths of 512 points, so the waveform data and synthetics must be cut down, and often, decimated. Care must taken to make sure that the final data seismogram have the same sampling interval as its corresponding synthetic seismogram. So, at this point you must carefully determine what sampling interval you will use in constructing synthetics and how to decimate synthetic and observed data so individual data channel/synthetic pairs agree in sampling interval. This can be a problem because it is easy to use a mixed data set consisting of BH (20 sps) and LH (1 sps) waveforms. The utilities for dealing with this problem assume that you may BH and LH data together. You are on your own with other data sets.

Suppose you will be constructing synthetic seismograms with a sampling interval of 0.2 sec, or 5 sps. That means you will have to decimate the observed BH waveform data using a decimation factor in SAC of 4. Conversely, you will have to decimate the synthetic seismograms by a factor of 5 to get them down to 1 sps, appropriate for the LH data on hand, so both data and synthetics may need decimation. It is much more convenient, the way things are set up here, to calculate the synthetic seismograms with a single sampling interval, although this could be changed with a little work.

A little more analysis with SAC is necessary before windowing and decimation can occur. Bring up all of your good waveforms in a SAC window and pick the onset time of the P or S wave. Be careful because this is a critical analysis choice that will affect the stability and veracity of the inversion. Onset times are marked using the T0 marker in the "ppk"

command of SAC. Remember to write over your data file to save the time pick.

The C Shell **window_data.csh** is invoked to perform the windowing. Your choice of time window is input as a parameter and the time window is constructed to start 5 seconds before the T0 marker. Decimation factors are also input as well as a "factor" parameter which can be used to change the units of the data. Most GSN instrument responses correct to m/sec units, and after intergration, to m. **dishask**, the synthetics program, uses microns. Thus, a factor of 10^6 would be usefully multiplied with the data to match units. (As an aside, I noticed in a trial of this procedure that not all instrument responses were appropriately normalized. Some data amplitudes were off by very large numbers. Response processing should be carefully checked.)

window_data.csh will create a SAC macro file which will be used by SAC to process the data yet again. These final data waveforms will be stored in the data/invert subdirectory for use with **momvert**. The data waveform files will have the suffix ".win" appended to the original name.

Computation of the Greeen's Functions

Create synthetic Green's functions using **dishask.csh**. In the process of using the **create_stachan.csh** script, you will have been asked to provide receiver earth structure files for each station. A few simple earth structure files are provided under "teledb/emodels/receiver". These consist of "shield", "tectonic" and "oceanic" models. Each model file has the suffix ".res" appended to it denoting receiver earth structure. There are similar source earth models in teledb/emodels/source except the files have the suffix ".ses" for source earth structure. The PREM model is contained in "teledb/emodels/reference" is called "prem.ref". **dishask.csh** creates a datafile for the **dishask** fortran 77 program which actually does the computations. The synthetic Green's functions will be put in the directory "event/greens" (e.g., yunnan/greens).

Greens's Function Windowing and Decimation

The Green's functions must then be windowed using nearly the same procedure as the data. Use SAC to pick the onset times of the *.vss Green's functions as the T0 marker. (Only use the *.vss files. The other *.vds and *.clv) files will be automatically windowed by SAC.) Then process the data using the **window_greens.csh** script. The arguments are almost identical to that in **window_data.csh**. The windowed Green's function files do not have any special suffix appended to their names, but are simply overwritten. If a mistake is made here, rerun **dishask.csh**.

Moment Tensor Inversion

At last the Green's functions (for one source depth) and the data have been processed. Inversion can now proceed. **momvert_setup.csh** is provided to create a parameter control file for **momvert**, the inversion program. This is another somewhat tedious routine which asks questions about what you want to invert for and so on. Finally, **momvert.csh** puts it all together and runs the **momvert** program. To invert for other source depths, you have to rerun **dishask.csh**, pick T0 on the *.vss Green's functions, rerun **window_greens.csh** and, possibly, **momvert_setup.csh**.

In case you would like to do a little trial-and-error modeling of the data, a C Shell script called **synthetic.csh** has been written to run the **dishask** program for making synthetics for particular source models. I ran out of command line parameters for this script so you must go into the script and edit particular entries that are written to the input file to **dishask**. Also, the event.stachan file should be rebuilt, preferably with another name to reflect the fact that synthetics are being computed and not Green's functions. (The mnvert parameter in the last question of **create_stachan.csh** must be set to 0, not 1). A fast way to make an appropriate event.stachan file is to edit this entry in a text editor.

Random Technical Points

momvert:
The arrays in momvert are dimensioned for a total of 4000 data points. For example, 10 seismograms which are each 400 points long could be used in an inversion. Reducing the number of data points is the purpose of waveform decimation and the option in **momvert_setup.csh** for choosing an effective decimation in the inversion program.

20 time function elements may be specified. Time function element averaging works; use an odd number of elements if you want to average.

Inversion for station amplitude factors has not been checked and is not trustworthy. Do not use. Assume station factors of unity.

dishask:
The maximum length synthetic time series allowed is 2048 points. The program makes sure that the working number of points is some power of 2 for FFT use.

momplot:

Source code for this program, written by Jeff Barker, is in the teledb/src/momvert directory. It is an interactive program which computes synthetic seismograms from the Green's functions and the inversion result and plots data and synthetic around moment tensor focal mechanisms. This program will be available once I repair the data input formats and find the appropriate graphics libraries on our new system at Penn State. It is not available for the short course.

JSPC Software:

The DATASCOPE software is available from the IRIS/JSPC via anonymous ftp. The machine address is jspc.colorado.edu. You will need a big disk to hold it.

Acknowledgements

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Appendix

This appendix contains listings of the C Shell scripts which drive Fortran 77 programs, the SAC program, and the evalresp program. A complete listing of the source code for programs written here is available in the "teledb/src" directory.

```
#!/bin/csh   -f
#
#     Create_directory.csh - shell script to build directories
#           for teleseismic moment tensor inversion
#
if ($#argv != 1) then
      echo "Usage:  $0  {directory name}"
      exit
endif
#
mkdir  ./$1
mkdir  ./$1/data
mkdir  ./$1/data/raw
mkdir  ./$1/data/process
mkdir  ./$1/data/invert
mkdir  ./$1/sacplz
mkdir  ./$1/synth
mkdir  ./$1/greens
mkdir  ./$1/invert
mkdir  ./$1/db

exit
```

```
#!/bin/csh  -f
#
#      create_stachan.csh

#      Set up input file for the sctable.f program
#      Run sctable.f to produce a database file that will
#        be used in the dishask program

#      Note: $PSUMOM environmental variable is needed to
#             find all directories.  sctable.f will also
#             need db.wfdisc and SAC waveform files

if ($#argv != 3 ) then
    echo "Usage: $0 {dbold dbnew eventdir}"
    echo "Where,"
    echo "      dbold   = working database table name."
    echo "      dbnew   = new database table name."
    echo "       eventdir = event directory name."
    exit
endif

#      Set up directory info for the sctable program

set dbpath = ($PSUMOM/$3/db)
set datapath = ($PSUMOM/$3/data)
set recpath = ($PSUMOM/emodels/receive)

#      Write file-pathnames to file sctable.in

echo $dbpath > sctable.in
echo $datapath >> sctable.in
echo $recpath >> sctable.in

echo $1 >> sctable.in
echo $2 >> sctable.in

#      Run the sctable program to build a stachan database file for
#            each waveform of interest

sctable
```

```
#!/bin/csh  -f
#
#     dishask.csh

#         Set up input file for the dishask.f program
#         Run dishask.f to create synthetic Green's functions
#         for use in the inversion program

#         Note:  $PSUMOM environmental variable is needed to
#                 find all directories.  dishask.f will also
#                 need db.wfdisc and db.stachan files.  All
#                 Source, receiver and reference earth model
#                 files must also be available in the proper
#                 directories.

if ($#argv != 9 ) then
      echo "Usage: $0 {dbname eventdir refmodel srcmodel SACfile
      depth tau npts dt}"
      echo " where dbname      = working database name"
      echo "           eventdir = event directory name."
      echo "           refmodel = file name for the reference earth
                             model"
      echo "           srcmodel = file name for the source earth
                             model"
      echo "           SACfil    = rootname of output SAC files"
      echo "           depth     = source depth (km)"
      echo "           tau       = time width of triangular time
                             function element"
      echo "           npts      = number of samples in the synthetic
                             time series"
      echo "           dt        = time series time increment"
      echo "  "
echo "  Note, that a moment of 1.0e+25 is built into this calculation."
      exit

endif

#         Write SACfile root name to dishask.in

echo $5 > dishask.in

#         Set up directory info for the dishask program
set dbpath = ($PSUMOM/$2/db)
set srcpath = ($PSUMOM/emodels/source/$4)
set recpath = ($PSUMOM/emodels/receive)
```

```
set refpath = ($PSUMOM/emodels/ref/$3)
set grnpath = ($PSUMOM/$2/greens)

#        Write file-pathnames to file dishask.in

echo $dbpath  >> dishask.in
echo $srcpath >> dishask.in
echo $recpath >> dishask.in
echo $refpath >> dishask.in
echo $grnpath >> dishask.in

#        Write database name to file dishask.in

echo $1 >> dishask.in

#        Write default input data stream to dishask.in for computing
#        Green's functions

echo "1" >> dishask.in
echo " 0.  0.  0." >> dishask.in
echo "1.0  1.0  1.0  1.0          1.0  1.0 " >> dishask.in
echo "1.0e+25" $6 >> dishask.in
echo $7 "1" >> dishask.in
echo "1.0" >> dishask.in
echo $8 $9 >> dishask.in

#      Run the dishask program to create Green's functions for this
depth

dishask < dishask.in

#      All Done!
exit
```

```csh
#!/bin/csh   -f
#
#      momvert.csh

#      Run the Momvert program.
#
#      Note:  $PSUMOM environmental variable is needed to
#               find all directories.  gwindow.f will also
#               need the db.stachan file.

if ($#argv != 3 ) then
    echo " "
    echo "Usage: $0 {dbname eventdir parmfile}"
    echo "Where,"
    echo "     dbname   = database table name (as in dbname.waveparm)."
    echo "     eventdir = event directory name."
    echo "     parmfile = name of the Momvert parameter file."
    exit
endif

set invpath = ($PSUMOM/$2/invert)

cd $invpath

#      Set up directory info

set dbpath = ($PSUMOM/$2/db)

#      Write dbpath to file momvert.in

echo $dbpath > momvert.in

#      write database name to momvert.in

echo $1 >> momvert.in

#      write parameter filename to momvert.in

echo $3 >> momvert.in

#      Run the Momvert program
momvert < momvert.in
```

```
#!/bin/csh  -f
#
#      momvert_setup.csh

#        Set up parameter files and waveform info files for the
#        Momvert program.
#
#        Note:  $PSUMOM environmental variable is needed to
#                  find all directories.  gwindow.f will also
#                  need the db.stachan file.

if ($#argv != 4 ) then
     echo " "
     echo "Usage: $0 {dbname eventdir sacroot parmfile}"
     echo "Where,"
     echo "          dbname   = database table name (as in
                              dbname.waveparm)."
     echo "          eventdir = event directory name."
     echo "          sacroot  = Root name of Green's functions Sac files."
     echo "          parmfile = name of the Momvert parameter file."
     exit

endif

#        Set up directory info

set dbpath = ($PSUMOM/$2/db)

#        Write Sacroot to file

echo $3 > momparm.in

#        Write dbpath to file momparm.in

echo $dbpath >> momparm.in

#        write database name to momparm.in

echo $1 >> momparm.in

#        write parmfile to file

echo $4 >> momparm.in

#        Run the mvertw program to create a dbname.waveparm file

mvertw < momparm.in
```

```
#       Run the momparm program to create a Momvert parameter file
#       Program will have interactive input.

momparm
```

```
#!/bin/csh   -f
#
#      prewave.csh

#      Set up input file for the prewave.f program
#      Run prewave.f to produce new database files and
#          SAC macro file for instrument response correction
#          in addition to making polezero files for each
#          channel
#      Run SAC to correct for instrument responses
#
#      Note:  $PSUMOM environmental variable is needed to
#                find all directories

if ($#argv != 5 ) then
    echo "Usage: $0 {dbold dbnew eventdir refmodel depth}"
    echo "Where"
    echo "      dbold    = working database table name."
    echo "      dbnew    = new database table name."
    echo "      eventdir = event working directory name."
    echo "      refmodel = spherical earth model (without .ref suffix)."
    echo "      depth    = source depth for travel time calculation." exit
endif

#      Set up directory info for the prewave program

set respath = ($PSUMOM/responses)
set plzpath = ($PSUMOM/$3/sacplz)
set dbpath = ($PSUMOM/$3/db)
set emodpath = ($PSUMOM/emodels)
set datapath = ($PSUMOM/$3/data)

#      Write to file prewave.in

echo $respath > prewave.in
echo $plzpath >> prewave.in
echo $dbpath >> prewave.in
echo $emodpath >> prewave.in
echo $datapath >> prewave.in

#      write database names to prewave.in

echo $1 >> prewave.in

echo $2 >> prewave.in
```

```
#        specify reference earth model

echo $4 >> prewave.in

#          Specify source depth for travel time computation here

echo $5 >> prewave.in

#          Calculate source origin time and put into prewave.in
echo $dbpath > rdorig.in
echo $1 >> rdorig.in
set torgin = `rdorigin < rdorig.in`
set torg = `epoch $torgin`
echo $torg[2] >> prewave.in
echo $torg[3] >> prewave.in
echo $torg[4] >> prewave.in


#      Run the prewave program to:
#             Determine source-receiver distance
#             Calculate· P, S wave travel times
#             Compute polezero file
#             produce new wfdisc file
#             Produce a new phase associate file
#             Write a SAC macro for instrument correction

prewave < prewave.in

#        Run the plzero.script in the sacplz directory

cd $plzpath
chmod 755 plzero.script
plzero.script

#        Run the SAC program to correct data for instrument response

cd $datapath/raw
sac < sac.process.in

#        Make copies of the old database files into new database

cp $dbpath/$1.origin  $dbpath/$2.origin
cp $dbpath/$1.site  $dbpath/$2.site

#        All done!

exit
```

```
#!/bin/csh   -f
#
#       rotate.csh

#       Set up input file for the rotwave.f program
#       Run rotwave.f to produce new database files and
#           SAC macro file for vector rotations

#       Run SAC to correct for instrument responses
#
#       Note:  $PSUMOM environmental variable is needed to
#                find all directories.  rotwave.f will also
#                need db.wfdisc and db.origin files to correct
#                horizontal data channels.

if ($#argv != 3 ) then
     echo "Usage: $0 {dbold dbnew eventdir}"
     echo "Where,"
     echo "       dbold   = working database table name."
     echo "       dbnew   = new database table name."
     echo "        eventdir = event directory name."
     exit
endif

#       Set up directory info for the rotwave program

set dbpath = ($PSUMOM/$3/db)
set datapath = ($PSUMOM/$3/data)

#       Write  to  file  rotwave.in

echo $dbpath >> rotwave.in
echo $datapath >> rotwave.in

#       write database names to rotwave.in

echo $1 >> rotwave.in
echo $2 >> rotwave.in


#       Run the rotwave program to:
#               Determine if there are 2 horizontal components,per station
#               Check SAC header for sufficient information for rotation
#               Write a SAC macro for data rotation
#               Produce a new *.wfdisc file of final processed data
```

```
rotwave  <  rotwave.in

#          Run the SAC program to correct data, if needed, and then
#              rotate

cd  $datapath/process
sac  <  sac.rotate.in

#          Make copies of the old database files into new database

cp  $dbpath/$1.origin  $dbpath/$2.origin
cp  $dbpath/$1.site  $dbpath/$2.site


#          All done!

exit
```

```
#!/bin/csh   -f
#
#      synthetic.csh

#      Set up input file for the dishask.f program
#      Run dishask.f to create synthetic seismograms.

#      Edit the contents of this script to input appropriate
#      source parameters

#      Note:  $PSUMOM environmental variable is needed to
#             find all directories.   dishask.f will also
#             need -db.wfdisc and db.stachan files.   All
#             Source, receiver and reference earth model
#             files must also be available in the proper
#             directories.

if ($#argv != 9 ) then
     echo "Usage: $0 {dbname eventdir refmodel srcmodel SACfile depth
     tau npts dt}" echo "  where dbname   = working database name"
       echo "            eventdir = event directory name."
       echo "            refmodel = file name for the reference earth model"
       echo "            srcmodel = file name for the source earth model"
       echo "            SACfil   = rootname of output SAC files"
       echo "            depth    = source depth (km)"
       echo "            tau      = time width of triangular time function
                                    element"
       echo "            npts     = number of samples in the synthetic time
                                    series"
       echo "            dt       = time series time increment"
       echo "  "
       echo "  Note, that an appropriate dbname.stachan file must exist with"
       echo "            the mnvert parameter set to 0 to calculate a
       synthetic."
       exit

endif

#      Write SACfile root name to dishask.in

echo $5 > dishask.in

#      Set up directory info for the dishask program
set dbpath = ($PSUMOM/$2/db)
set srcpath = ($PSUMOM/emodels/source/$4)
```

```
set recpath = ($PSUMOM/emodels/receive)
set refpath = ($PSUMOM/emodels/ref/$3)
set grnpath = ($PSUMOM/$2/synth)

#       Write file-pathnames to file dishask.in

echo $dbpath  >> dishask.in
echo $srcpath >> dishask.in
echo $recpath >> dishask.in
echo $refpath >> dishask.in
echo $grnpath >> dishask.in

#       Write database name to file dishask.in

echo $1 >> dishask.in

#       Modify these input data streams to dishask.in for computing
#         source models with arbitrary parameters.

#       nfstyp =0, dislocation parameters,  =1, moment tensor

echo "0" >> dishask.in

#       strike, dip, and rake in degrees


echo " 30. 40.  60." >> dishask.in

#       moment tensor elements,  m11,m12,m13,m22,m23,m33

echo "1.0  1.0  1.0  1.0  1.0  1.0 " >> dishask.in

#       seismic moment dyne/cm and depth

echo "1.0e+25" $6 >> dishask.in

#       tau for triangle series and number of triangles in time function

echo $7 "5" >> dishask.in
#        input the values of the triangle series, the area of the time

#        function will be normalized in the program.

echo "0.5 0.4 0.3 0.2 0.1" >> dishask.in

#        input npts and delt-t for time series

echo $8 $9 >> dishask.in
```

```
#      Run the dishask program to calculate synthetics

dishask < dishask.in
#      All Done!
exit
```

```csh
#!/bin/csh   -f
#
#      window_data.csh

#      Set up input file for the dwindow.f program
#      which will create a SAC macro file for windowing,
#      filtering and decimation of waveform data.

#      Run SAC to perform this stuff.
#
#      Note:  $PSUMOM environmental variable is needed to
#             find all directories.  dwindow.f will also
#             need db.wfdisc and db.stachan files.

if ($#argv != 7 ) then
    echo " "
    echo "Usage: $0 {dbname eventdir corner factor twindow decbh declh}"
    echo "Where,"
    echo "        dbname   = database table name (as in dbname.wfdisc)."
    echo "        eventdir = event directory name.  Will construct name"
    echo "                   PSUMOM/datadir/data."
    echo "        corner   = corner frequency for high pass butterworth
                             filter."
    echo "        factor   = constant multiplicative factor to convert
                             units."
    echo "        twindow  = data waveform time window wanted.  Will
                             assume"
    echo "                   5 seconds before t0 pick time as start time."
    echo "        decbh    = decimation factor that SAC will use to
                             decimate"
    echo "                   the 20sps data.  Use a value of 1 for no
                             decimation."
    echo "        declh    = decimation factor that SAC will use to
                             decimate"
    echo "                   the 1sps data.  Use a value of 1 for no
                             decimation."
    exit
endif

#      Set up directory info for the dwindow program

set dbpath = ($PSUMOM/$2/db)
set datapath = ($PSUMOM/$2/data)
```

```
#       Write to file dwindow.in

echo $dbpath > dwindow.in

echo $datapath >> dwindow.in

#       write database names to dwindow.in

echo $1 >> dwindow.in

#       Write SAC parameters to file, also

echo $3 $4 $5 $6 $7 >> dwindow.in

#       Run the dwindow program to create a SAC macro file

dwindow < dwindow.in

#       Run the SAC program to window the data

cd  $datapath/process

sac < sac.dwindow.in

#       All done!

exit
```

```
#!/bin/csh   -f
#
#      window_greens.csh

#      Set up input file for the gwindow.f program
#      which will create a SAC macro file for windowing,
#      filtering and decimation of waveform Green's functions.

#      Run SAC to perform this stuff.
#
#      Note:  $PSUMOM environmental variable is needed to
#             find all directories.  gwindow.f will also
#             need the db.stachan file.

if ($#argv != 8 ) then
      echo " "
      echo "Usage: $0 {dbname eventdir SACname corner factor twindow
                        decbh declh}"
      echo "Where,"
      echo "       dbname   = database table name (as in dbname.wfdisc)."
      echo "       eventdir = event directory name.  Will construct name"
      echo "                  PSUMOM/eventdir/greens."
      echo "       SACname  = Root of Green's function filenames used in"
      echo "                  Dishask computations."
      echo "       corner   = corner frequency for high pass butterworth
                              filter."
      echo "       factor   = constant multiplicative factor to convert
                              units."
      echo "       twindow  = data waveform time window wanted.  Will
                              assume"
      echo "                  5 seconds before t0 pick time as start
                              time."
      echo "       decbh    = decimation factor that SAC will use to
                              decimate the BH"
      echo "                  data.  Use a value of 1 for no decimation."
      echo "       declh    = decimation factor that SAC will use to
                              decimate the LH"
      echo "                  data.  Use a value of 1 for no decimation."
      exit

endif

#      Input SAC root name

echo $3 > gwindow.in
```

```
#       Set up directory info for the dwindow program
set dbpath = ($PSUMOM/$2/db)
set grnpath = ($PSUMOM/$2/greens)

#       Write to file gwindow.in

echo $dbpath >> gwindow.in

echo $grnpath >> gwindow.in

#       write database name to gwindow.in

echo $1 >> gwindow.in

#       Write SAC parameters to file, also

echo $4 $5 $6 $7 $8>> gwindow.in

#       Run the dwindow program to create a SAC macro file

gwindow < gwindow.in

#       Run the SAC program to window the Green's functions

cd $grnpath

sac < sac.gwindow.in


#       All done!

exit
```